PRISM AND LENS MAKING

TWYMAN

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A Text Book for Optical Glassworkers

BY

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PREFACE

This book describes methods which are in use in the optical workshops of Adam Hilger Limited for making high quality prisms and lenses.

Optical firms are reticent about their methods and it may well be that we are considerably behind some of our fellow-manufacturers in just those directions where we suppose ourselves to be leading. Certain of the methods here described are certainly antiquated, even if others have only recently been developed by us, but of one thing the reader can be assured—namely, that these methods and machines will enable even an unskilled worker, after a short period of training under competent supervision, to produce work of first quality as far as definition and accuracy of angle are concerned.

I hope that those manufacturers who may be using other, and perhaps better, methods may be willing to give me the benefit of a full knowledge of them. A reliable and complete text might in that way become available which would raise opticians to a level of proficiency not attained in our generation.

The bibliographical references have been incorporated in the Name Index where the system used in the Royal Society's Publications has been followed (*i.e.* references in the text are by the author's name and date of publication—thus: Jones & Homer (1941)). There are, as exceptions to this, some brief Bibliographical Notes at the close of Chapter I, and a special Bibliography concerning the Hilger Interferometers, placed for convenience at the close of Chapter IX.

The section on the metallisation of metals was kindly written for me by Dr. K. M. Greenland of the British Scientific Instrument Research Association.

During the preparation of the book I have had much help from co-workers of mine at Hilgers, in particular Mr. S. J. Underhill, Head of the Optical Department; Mr. J. W. Perry, Chief Computer and Head of Applied Optics Department; Mr. A. Green, Mr. A. Pope and Mr. A. S. Henderson, who are in charge of various optical shops; but it would not be correct to assume that any errors or grave omissions are other than my own.

My thanks are also due to Mr. T. L. Tippell, whose careful proof-reading has resulted in the correction of many errors and crudities of diction.

My acknowledgments are also due to the publishers of the *Encyclopaedia Britannica* for permission to use extensively my article in the 14th Edition on "The Manufacture and Testing of Lenses", and to my co-Directors on the Board of Adam Hilger Ltd. for permission to publish much information hitherto private to the Company.

F. TWYMAN.

CONTENTS

APPENDICES

CHAPTER I

HISTORICAL

(The references by number are to the Bibliographical Notes to Chapter I, page 9.)

§1. As with most of the useful arts, the development of lens making has been in an order the reverse of what the scientific man feels to be logical. Instead of first studying the principles of the process, then putting the process into operation, and then finding a use for the product—a course followed by the science-born electrical industry—man first discovered some optical uses of accidentally produced lens-shaped bodies, and only then set himself deliberately to make lenses, leaving till quite recent times the study of the process of lens polishing.

§2. The references of Pliny and other ancient writers show quite clearly that burning glasses were known to them in the shape of glass spheres filled with water; and passages from Greek and Roman writers have been cited as showing that they knew of the magnifying properties of lenses, or at least of such glass spheres filled with water. The very thorough account of the subject by Wilde (1838–43)[1] denies to the ancients all knowledge of spectacle lenses whether for short or long sight, or indeed of any kind of lenses, if we except the spheres of glass filled with water referred to above; and maintains that the lens-shaped glasses or crystals which have been found from time to time among the relics of departed civilisations were made by polishers of jewels for purposes of ornament. Mach (1926), on the other hand, seems to tend, on the whole, to the opinion that a few archaeological objects which have been found were made, and intended to be used, as lenses.

§3. We must come to the end of the thirteenth century for the first authentic mention of the use of lenses, which appears to be that of Meissner (1260–80) when he expressly states that old people derive advantage from spectacles (Bock, 1903).[2] In the archives of the old Abbey of Saint-Bavon-le-Grand, the statement is found that Nicolas Bullet, a priest, in 1282 used spectacles in signing an agreement (Pansier, 1901).[3] The first picture in which spectacles are known to have appeared is by Tomaso de Modena, in the Church of San Nicola in Treviso, and is of date 1360 (Oppenheimer, 1908).

§4. In a sermon delivered on the 23rd of February, 1305, Giordano da Rivalto stated that "it was only twenty years since the art of making spectacles was discovered" (Pansier, 1901). It may be accepted, from this and like evidence, that the use of spectacles dates from a little

prior to 1280; earlier than which the industry of a host of enquirers has produced no certain evidence that a lens of any kind had ever been intentionally made by man for use as such.

§5. If at an earlier date the very existence of lenses is unproved, an account of their manufacture cannot be expected, and the present writer has found no account of how lenses were made until 1585 (about) when William Bourne[4] (*c.* 1585) gives an account, very imperfect, but yet sufficient to show that processes were then in use very like those still extant. He says (of spectacle lenses), "These sortes of glasses ys grounde upon a toole of Iron made of purpose, somewhat hollowe, or concave inwardes. And may be made of any kynde of glasse, but the clearer the better. And so the Glasse, after that yt ys full rounde, ys made fast with syman uppon a small block, and so ground by hand untill yt ys bothe smoothe and allso thynne, by the edges, or sydes, but thickest in the middle."

Nothing else is said by him of the materials, tools, or method of working.

§6. Baptista Porta

Very different is the account given by Baptista Porta of Naples (1591) in his famous book on Natural Magic—a technical encyclopaedia embracing subjects as diverse as optics, magnetism, cosmetics, cooking, alchemy, pharmacy, and practical jokes. Among much that is trivial, debased and revolting is also to be found much, like his description of optical polishing, which shows a keen quest after knowledge and accurate knowledge of a singularly wide range of subjects. The following extract is from Book 17, Chapter XXI. in the English translation published in 1658, but the matter is identical with the Latin edition of 1591. The translation has, however, rendered the original "pilae vitreae"—the phrase employed (as by Pliny) to describe a *hollow glass ball*—by "Glass-balls"; and the reader must bear this in mind if he wishes to follow the description correctly.

§7. "In Germany there are made Glass-balls, whose diameter is a foot long, or there abouts. The Ball is marked with the Emrilstone round and is so cut into many small circles, and they are brought to Venice. Here with a handle of wood are they glewed on, by Colophonia melted. And if you will make Convex Spectacles, you must have a hollow iron dish, that is a portion of a great sphaere, as you will have your spectacles more or less Convex; and the dish must be perfectly polished. But if we seek for concave spectacles, let there be an Iron ball, like to those we shoot with Gun-powder from the Great Brass Cannon; the superficies whereof is two, or three foot about. Upon the Dish or Ball, there is strewed white-sand, that comes from Vincentia, commonly called Saldame, and with water it is forcibly rubbed between our hands, and that so long until the superficies of that circle shall receive the form of the Dish, namely a Convex superficies or else a Concave superficies upon the superficies of the Ball, that it may fit the superficies of it exactly. When that is done heat the handle at a soft fire, and take off the spectacle from it, and join the other side of it to the same handle with Colophonia, and work as you did before, that on both sides it may receive a Concave or Convex superficies, then rubbing it over again with the Powder of Tripolis that it may be exactly polished; when it is perfectly polished, you shall make it perspicuous thus. They fasten a woollen-cloth upon wood; and upon this they sprinkle water of Depart, and powder of Tripolis; and by rubbing it diligently, you shall see it take a perfect glass. Thus are your great Lenticulars and spectacles made at Venice."

§8. Cherubin d'Orlèans (1671)

In 1671 appeared the well-known book by a Père Cherubin d'Orlèans which not only deals with optics, with telescopes (including binoculars) and microscopes, their theory and construction and use, but with the making of lenses, the working of lenses and of various machines invented by himself for that purpose to lessen the labour and increase the speed and accuracy of polishing lenses for telescopes. This latter part of the book consists of eighty-two pages and many illustrations (approx. 35,000 words). These descriptions are so good, and show such thoughtful personal knowledge of the subject, that they would be suitable to place in the hands of an optical apprentice today.

The materials which he used were so nearly like those which are still widely used and are described so well that a free translation of what he says will not be out of place, if only that one may realise how little that is fundamentally new has been discovered in the interim if we except the processes which have been introduced in the twentieth century.

His materials were—for the tools, iron and brass; for the mallets (molettes) for holding the lenses, lead, tin or (which he prefers) copper. He gives full particulars for making the patterns for casting, for making the moulds, turning and grinding the tools. For turning the tools he invented practical lathes.

Of the cement for attaching the lens to the mallet, he says that some make it of best black pitch (which must not be burnt) and sifted ashes of vine cuttings; but that he prefers to add (to the pitch) a fourth part of good grape jelly and, in place of the ashes, finely ground ochre or whiting.

As a good material for grinding he recommends broken grind stones. These are graded by putting the powder into a large vessel full of water, agitating it well, letting it settle a little for the coarse particles to settle out, and then pouring off quickly into another vessel most of the liquid

which will carry with it the finer material. This one allows to settle entirely, gently pouring off the remaining liquid. The sediment (containing the useful grains) is treated in this way several times, and in this way one separates out the grains of several degrees of "strength" which are kept separately for use according to the nature of the work. For polishing material he used Tripoli (preferably that of Germany) or "potée d'estain" (putty powder).

Of the Tripoli he says that the lightest is the best. If of good quality it can be used in the lump, as Nature produces it, otherwise ground with brandy or (failing that) white wine, and kept in a closed jar of water to soften for four or five months. It can be sun-dried, and used in lumps, or used wet straight from the jar.

The putty powder he prefers is that made by calcining tin (he gives detailed instructions for its preparation). The glass was provided by broken Venice mirrors, and was thus in a form polished on both sides and suitable for examination.

He claims to have made an improvement in the mode of polishing in that he stretched across the concave tool, which he had used for grinding, a soft thin piece of leather of uniform thickness, fixing it in position with a ring which just fitted the circumference of the tool. On this he rubbed his lens, pressing it down so that the leather was forced to fit the surface of the grinding tool. Another way he used was to coat the surface of the grinding tool with paper, the latter being pasted in position with many precautions to avoid wrinkling or other inequalities of the surface. This paper he moistened with Tripoli powder and so used for polishing. But these methods do not seem superior to that described by Porta. Of the machines he describes as invented by himself several may well have been the progenitors of some in use today. One of them may be mentioned in which the optical tool, mounted on a vertical spindle, is rotated by means of a rope and suspended weight so that the operator's hands are free. The tool is turned accurately to the desired radius by means of a radius arm pivoted at one end, and bearing a turning tool at the other, by means of which the tool is turned to the desired concavity. The same machine is used in grinding and polishing the glasses, the latter being held in the hand as in free-hand working, and the present writer has found no earlier description of machines for turning the tools or for grinding and polishing lenses.

§9. Hooke and Newton

About this time Hooke was working on the microscope (Hooke 1667). He describes a way of making microscope objective lenses; he drew a piece of broken Venice glass in a lamp into a thin thread, then held the end of this thread in a flame till a globule of glass was formed. He then polished a flat surface on the thread side of the

globule, first on a whetstone then on a smooth metal plate with Tripoli; but these lenses being too small he used good plano-convex object glasses, and there is no indication that he made these himself.

§10. The great Dutch microscopist, Leeuwenhoek (1719), made his own lenses, but left no account of his methods. He says in a letter to Leibnitz dated the 28th of September, 1715: "As to your idea of encouraging young men to polish glass—as it were to start a school of glass polishing—I do not myself see that would be of much use. Quite a number, who had time on their hands at Leyden, became keen on polishing glasses, owing to my discoveries; indeed there were three masters of that art in that town, who instructed students who were interested in such things. But what was the result of their labour? Nothing at all, so far as I have learnt.

"Now to every study the proposed object is this: to acquire wealth by knowledge, or celebrity by reputation for learning. But that is not to be gained either by polishing glasses or by discovering abstruse things. And then I am convinced hardly one in a thousand is properly fitted to take up this study for much time is consumed in it and money is wasted, and if one is to make any progress in it one's mind must be for ever on the stretch, thinking and speculating. The majority of men are not sufficiently inflamed with the love of knowledge for that. Indeed, many whom it by no means becomes, do not hesitate to ask, What does it matter whether we know these things or not?"

§11. Newton (1721) makes some important remarks on polishing, which though referring to mirrors are also applicable to lenses; and appears to have been the first to use pitch for polishing, an innovation of the very greatest importance.

"The Polish I used was in this manner. I had two round Copper Plates each five inches in diameter, the one convex, the other concave, ground very true to one another. On the convex I ground the Object-Metal or Concave which was to be polished, till it had taken the figure of the Convex and was ready for the Polish. Then I pitched over the convex very thinly, by dropping melted Pitch upon it and warming it to keep the Pitch soft, whilst I ground it with the concave copper, wetted to make it spread evenly all over the convex. Thus by working it well I made it as thin as a Groat, and after the convex was cold I ground it again to give it as true a figure as I could. Then I took Putty which I had made very fine by washing it from all its grosser particles, and lay a little of this upon the pitch, I ground it upon the Pitch with the concave Copper till it had done making a noise; and then upon the pitch I ground the Object-Metal with a brisk motion, for about two or three minutes of time, leaning hard upon it. Then I put fresh putty upon the Pitch and ground it again till it had done making a noise, and afterwards ground the Object-Metal upon it as before. And this work

I repeated till the Metal was polished, grinding it the last time with all my strength for a good while together, and frequently breathing upon the pitch to keep it moist without laying on any more fresh Putty. The object-metal was two inches broad and about one third part of an Inch thick, to keep it from bending. I had two of these Metals, and when I had polished them both I tried which was best, and ground the other again to see if I could make it better than that which I kept. And thus by many trials I learn'd the way of polishing, till I made those two reflecting Perspectives I spake of above. For this Art of Polishing will be better learned by repeated Practice than by my description. Before I ground the Object-Metal on the Pitch, I always ground the Putty on it with the concave Copper till it had done making a noise, because if the Particles of the Putty were not by this means made to stick fast in the Pitch, they would by rolling up and down grate and fret the Object-Metal and fill it full of little holes.

"But because metal is more difficult to polish than Glass, and is afterwards very apt to be spoiled by tarnishing and reflects not so much Light as Glass quick-silvered over does: I propound to use instead of the Metal, a Glass ground concave on the foreside, and as much convex on the back-side, and quicksilvered over on the convex side. The Glass must be everywhere of the same thickness exactly. Otherwise it it will make objects look coloured and indistinct. By such a Glass I tried about five or six Years ago to make a reflecting telescope of four Feet in length to magnify about 150 times, and I satisfied myself that there wants nothing but a good Artist to bring the design to perfection. For the glass being wrought by one of our London Artists after such a manner as they grind Glasses for Telescopes, tho' it seemed as well wrought as the object-glasses use to be, yet when it was quick-silvered, the Reflexion discovered innumerable Inequalities all over the Glass. And by reason of these Inequalities, Objects appeared indistinct in this Instrument. For the errors of reflected Rays caused by an Inequality of the Glass are about five times greater than the Errors of refracted rays caused by the like Inequalities. Yet by this Experiment I satisfied myself that the Reflexion on the concave side of the Glass, which I feared would disturb the Vision, did no sensible prejudice to it, and by consequence that nothing is wanting to perfect these Telescopes but good Workmen who can grind and polish Glasses truly spherical. An Object-Glass of a fourteen Foot Telescope made by an Artificer at London, I once mended considerably by grinding it on Pitch with Putty, and leaning very easily on it, in the grinding, lest the Putty should scratch it. Whether this way may not do well enough for polishing these reflecting Glasses, I have not yet tried. But he that shall try either this or any other way of polishing which he may think better, may do well to make his Glasses ready for polishing by grinding them

without that violence wherewith our London workmen press their Glasses in grinding. For by such violent pressure, Glasses are apt to bend a little in the grinding, and such bending will certainly spoil their figure."

Herschel, Fraunhofer, Lord Rosse

§12. Some optical grinding and polishing machinery appears to have been made and used early in the seventeenth century. Dr. C. A. Crommelin (1929) describes and illustrates machines made by Descartes, Huygens, Hooke, Helvelius and others.

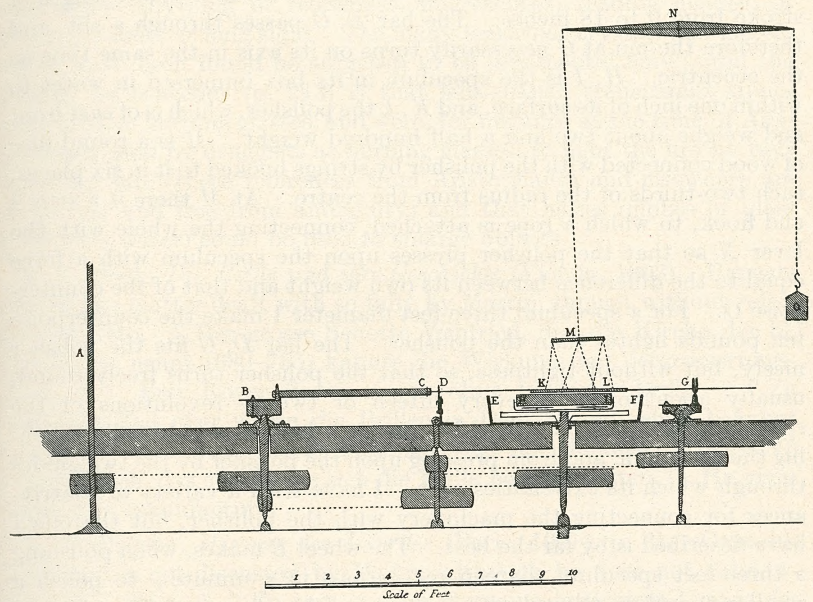

Fig. 1. Lord Rosse's Polishing Machine.

Herschel (1912) in 1774 used a pitch polisher for polishing the speculum mirrors, some of them very large, for his telescope. He mentions the polishing operation having been carried out by ten men on one occasion. He gave an account of the polishing of a large speculum by a machine which he made to avoid the necessity of employing so many men; but no very clear description of the machine was included, nor any illustration of it.

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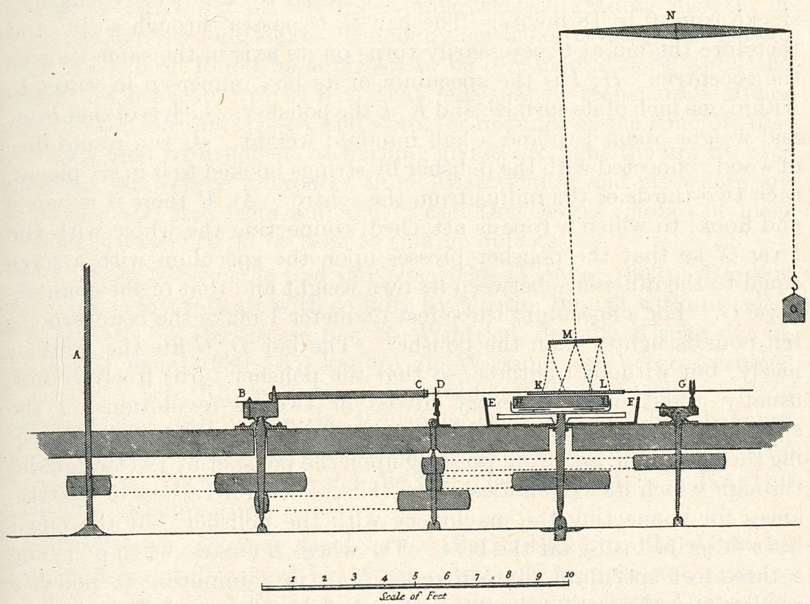

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A published account (Dévé 1936), however, attributes their earliest use to the French firm of Laurent (now Messrs. Jobin et Yvon) about fifty years ago.

§14. Finally, in what we may still call the historical period, Lord Rosse (Parsons, 1926) (then bearing the title of Lord Oxmantown—he succeeded to the title of Earl of Rosse in 1841) described before the Royal Society a machine for polishing large specula.

" *A* is a shaft connected with a steam-engine ; *B* an eccentric, adjustable by a screw-bolt to give any length of stroke from 0 to 18 inches ; *C* a joint ; *D* a guide ; *E*, *F* a cistern for water, in which the speculum revolves ; *G* another eccentric, adjustable like the first to any length of stroke from 0 to 18 inches. The bar *D*, *G* passes through a slit, and therefore the pin at *G* necessarily turns on its axis in the same time as the eccentric. *H*, *I* is the speculum in its box immersed in water to within one inch of its surface, and *K*, *L* the polisher, which is of cast iron, and weighs about two and a half hundred weight. *M* is a round disc of wood connected with the polisher by strings hooked to it in six places, each two-thirds of the radius from the centre. At *M* there is a swivel and hook, to which a rope is attached, connecting the whole with the lever *N* so that the polisher presses upon the speculum with a force equal to the difference between its own weight and that of the counterpoise *O*. For a speculum three feet diameter I make the counterpoise ten pounds lighter than the polisher. The bar *D*, *G* fits the polisher nicely, but without tightness, so that the polisher turns freely round, usually about once for every fifteen or twenty revolutions of the speculum, and it is prevented by four guards from accidentally touching the speculum, and from pressing upon the polisher by the two guides through which its extremities pass. I have tried a variety of contrivances for connecting the machinery with the polisher, but the one I have described is by far the best. The wheel *B* makes, when polishing a three-feet speculum, sixteen revolutions in a minute ; to polish a smaller speculum the velocity is increased by changing the pulley on the shaft *A*."

In the course of the same papers he describes the method of preparation of his rouge (Parsons 1926, p. 98) by calcination, at a dull red heat, of peroxide of iron produced as a precipitate with ammonia water from a dilute solution of iron sulphate. It is of interest to note that Lord Rosse was the father of Sir Charles Parsons, of steam turbine fame.

§15. These steps in the development of the existing methods of making lenses must suffice, but it must be added that the descriptions which have come down to us very possibly leave unnamed the workers to whom the methods are due ; methods which probably were originally derived from the very ancient art of polishing precious stones.

BIBLIOGRAPHICAL NOTES ON CHAPTER I

1. Th. Henri Martin, " Sur des instruments d'Optique faussement attribués aux anciens par quelques savants modernes," *Bulletino di Bibliografia e di Storia delle Scienze matematiche e fisike* (Roma). Vol. IV., pp. 165–238, 1871. The evidence discussed by Martin is in considerable part the same as that to be found in E. Wilde, *Geschichte der Optik* (Berlin, 1st vol. 1838, and 2nd vol. 1843) : but Martin's treatment is by far the fuller. M. Martin, in this entertaining paper, reviews comprehensively the evidence that the ancients were acquainted with certain optical instruments, and shows that there is no reliable evidence that they knew anything of telescopes, microscopes, reading glasses, or lenses for short or long sight. The many lenticular crystals and glasses which have been found he supposes to be ornamental only ; and the utmost he concedes (p. 213) is that lens-shaped transparent stones were used as burning glasses, and were, for instance at the time of Aristophanes, sold by druggists as burning glasses, to light the fire by rays from the sun, (these references from Aristophanes and elsewhere are very clear and free from ambiguity) and that lenses (globes of glass filled with water) could be used to enlarge objects.

2. E. Bock, *Die Brille und ihre Geschichte* (Vienna, 1903). Repeats part of the matter dealt with so fully by Martin, though without reference thereto. " Der grosse Schotte Winfried, den die Kirche der hl. Bonifazius nennt (680–755) kannte die Wirkung der Vergrosserungsgläser." " Erst Roger Bacon . . . erwähnt 1276 die Brille." " Zu derselben Zeit aber waren die Brillen in Deutschland schon bekannt den in der Sammlung der Minnesanger sagt der Meissner (1260–1280) ausdrucklich, das alte Leute sich die Brille bedient hätten." He gives nothing of manufacture.

3. P. Pansier, *Histoire des Lunettes* (Paris, 1901), p. 21. Contains little that is not discussed by Martin, although he does not acknowledge it. On p. 5, " En tout cas, les Romains ignoraient l'usage des verres convexes pour pallie aux inconvenients de la presbytie, puisque, au temoignage de Manni, Cicéron, Cornélius Nepos, Suétone, attestent que, lorsque, en vieillissant, la vue s'affaiblit, on n'a pas d'autre ressource que de se faire faire la lecture par un esclave " ; and later, " Les verres concaves paraissent avoir été complètement inconnus des anciens," and " Aucune de ces citations ne nous permet de conclure à l'usage des verres chez les anciens pour pallier aux anomalies de la vision."

(He exaggerates the optical defects of lenses of this kind. They could quite well be used as aids by engravers and so forth—and probably were so, in spite of the ignorance of such writers as Pliny, and such a keen observer as Galen, both of whom he cites.—F. T.)

4. William Bourne, *A Treatise on the properties and qualities of glasses for optical purposes* (MS. Lansd. Mus. Brit. 121). The treatise is undated, but in all probability was written in 1585 since the author refers to a book written by him seven years previously, which is thought to be his *Treasure for Travellers*, published in London 1578. A brief mention only of grinding in a hollow iron tool.

CHAPTER II

THE ELEMENTS OF SINGLE LENS WORKING

§16. The Process of Polishing a Single Lens

Let us first describe in outline the process of polishing a lens. The outline will be filled in later.

The processes and materials are subject to numerous modifications and of course the great majority of lenses are made in great numbers by mass production methods which will also be described later on, but the essential principles are largely the same.

The method we shall sketch in this chapter is still in actual use in the production of high quality work (with modifications according to the taste or knowledge of the individual workman). It is the lineal descendant of the earliest descriptions of lens polishing which are extant, but is all the better for that when used to illustrate the various processes involved.

§17. Let us suppose it is desired to make a bi-convex lens, that is, a lens which is convex on both sides. Starting with the block of glass obtained from the glass maker, a piece is sawn from it of approximately the size required. The saw may consist of a thin flat soft iron blade one foot in diameter, rotating to give a peripheral speed of from 1000 to 2500 ft. per minute.* The edge of the blade need not be serrated but is charged with small fragments of diamond (less than 1/100th of an inch across), preferably produced by crushing large diamonds between two hard steel surfaces.† The blade will last so charged for quite a long time, indeed, often until by some carelessness on the part of the worker the diamond is scraped out by a corner of the glass which is being sawn. A number of experiments were made by us to find the best speed of such a saw and it was found that for a blade of $14\frac{1}{2}$ in. diameter the peripheral speed should be 2750 ft. per minute. A properly charged blade should cut about 1000 sq. ins. of glass. The piece of glass thus sawn off the lump is then ground roughly to disc shape by being held against a horizontal circular plate of cast iron, say $3\frac{1}{2}$ ft. in diameter, rotating sixty times a minute. On this plate is smeared a mud made of carborundum and water, the carborundum being of the kind known as " 80 " (this means that the powder is about the size that will pass through a sieve having eighty meshes to the inch).

* Some competent authorities advocate a peripheral speed of 2000 metres per minute, provided ample coolant is supplied, the glass being rotated against the movement of the blade.

† Good descriptions of how to make, charge and use these blades are in Strong (1939), page 38, and the article by French in Vol. IV of Glazebrook's *Dictionary of Physics* (French 1923.)

§18. The glass piece being roughly finished to disc shape and to a little greater than the final thickness of the lens, it is transferred to a rotating concave dish—called a roughing tool—whose radius of curvature is approximately that desired on the lens, and on this the disc is rubbed, also with carborundum, until it fits the tool. The close agreement of the glass piece with the shape of the roughing tool may be verified by coating the inside of the tool with rouge and rubbing the piece upon it. "High spots" will then be clearly indicated by the rouge marks and may be corrected. The curve having been roughly produced on both sides (and the worker having taken care that the thickest place is in the middle, otherwise he might find it impossible to edge his lens centrally when made) it is transferred to a true tool.

§19. True tools are always kept in pairs, concave and convex. No roughing must be done in them as it is highly important that they should fit very closely and be truly spherical. To this end they require to be ground together with fine emery at frequent intervals. The trueing of the lens, which consists in producing a finely ground and accurately spherical surface of the right radius of curvature, differs in no way from the roughing except that it is conducted with greater care, and with finer grinding material. The lens is held in the hand (or, if it is too thin for convenient handling in this way, by being stuck with pitch on to a piece of glass, lead, or other convenient holder) and is rubbed over the surface of the trueing tool, care being taken to utilise every part of the tool as far as possible, so as not to grind it away unduly in any one place. The tool may be screwed to an upright post round which the workman slowly walks or, more conveniently, may itself slowly rotate. As the process proceeds the workman uses finer and finer emery.

§20. The first part of this process is called trueing and for it emery varying from 0·1 mm. to 0·05 mm. in average grain diameter is used. A later stage is called smoothing and is carried out in the same way with emery whose grains vary down to 0·01 mm. or even less if the worker is so fortunate as to have well-graded material so fine as that. As the worker proceeds he takes more and more care that his concave and convex tools accurately fit one another, this being a necessary condition for the success of the polishing process which is immediately to follow, and he is also careful that the emery should be evenly distributed over the whole surface of the tool. He also carefully wipes away from the rim of the tool any grains of coarser emery which might cause scratches if they found their way to mingle with the fine emery. The finer the emery, the smaller the quantity required (see §79).

§21. The lens having been smoothed on both sides, the next procedure is to make a polisher. Into the concave tool, which is warmed for this purpose, is poured melted pitch. While this is still warm the convex tool (used cold, and if necessary dipped into water once or twice

to cool it during the process) is used to press the pitch over the surface of the concave tool till it forms a thin coating adhering to the latter a little more than $\frac{1}{8}$ inch thick. The convex tool is moved about in the socket thus formed and wetted occasionally with cold water to prevent its sticking, while the concave tool is allowed to cool down.

A reticulation is then cut in the surface of the pitch so that its surface is broken into squares of about $\frac{1}{2}$ inch side. On to this is put a piece of cotton gauze, and the whole surface of gauze and pitch coated by means of a paint brush with wet jeweller's rouge which has been shaken up in water, the coarser particles allowed to sink to the bottom and the water poured off the top so that the portion used is a liquid paste free from very coarse particles. The gauze is of about twenty mesh to the inch.* The convex tool, being slightly warmed, is rubbed in the concave tool and presses the gauze into the surface of the pitch so that, when the gauze is pulled away, the entire surface of the pitch is covered with coarse and fine reticulations so that in polishing, the rouge may find its way rapidly along the channels thus formed, to the whole surface which is being polished. When, in course of polishing, these reticulations disappear, they are renewed in the same way.

In the polisher thus formed the glass is rubbed about by hand until it is polished. The working should be distributed all over the polisher to prevent rapid distortion of the latter. For the best work a frequent reforming of the polisher by the application of the warm convex tool is necessary in order that the curve produced in the surface of the glass should be accurately spherical and of the correct radius of curvature. The time of the polishing operation may, with good fortune, approximate to an hour. It is not likely to be hastened by neglecting the care of the tools and of the polisher, nor is it the most energetic worker who will produce a perfectly polished surface most quickly.

§22. The whole of the above process having been carried out on both sides, one has a complete bi-convex lens. All that now remains is to centre and edge it. A piece of brass tube a little smaller than the required diameter of the lens is screwed on to the nose of a lathe and accurately trued. On this tube the lens is stuck by means of warm pitch. The workman now observes the reflections of any convenient object in the two surfaces of the lens. If the lens is rotating truly both these reflections will be motionless, and the worker adjusts the lens on the chuck until this condition is arrived at. When that is done he pours cold water over the lens and tube until they are cool and the pitch becomes relatively hard and unyielding, and while it is in this condition he brings a brass plate against the edge of the lens, feeding in trueing emery in the usual condition of mud until the lens is edged truly circular and of the correct diameter.

* Mosquito netting is very suitable.

§23. This simple method of hand polishing is still in use to produce work of the very highest class, but has long been discarded for production in quantity.

This is an appropriate place to recommend the reader to the section on laboratory optical work in *Modern Physical Laboratory Practice*, by John Strong (London: Blackie & Son, Ltd., 1940). It deals with a variety of optical operations including some of those described here, all treated with reference to manufacture in a laboratory workshop. The descriptions are excellent and illustrated with numerous clear and well-selected illustrations, and many of the hints will be found useful to learners and experts alike. The article by J. W. French on "The Working of Optical Parts" in Volume IV of Glazebrook's *Dictionary of Applied Physics* (1923) is the best summary I know from the point of view of manufacture.

§24. Another book full of useful information is *Le Travail des Verres d'Optique de Precision*, by Col. Charles Dévé (Paris, 1936: Revue d'Optique théorique et instrumentale). The character of this book is well described by the author in his "avertissement".

"It is not a manual for beginners. It is a *résumé* of the technological training which is given to the apprentices of the Trade School for Optical Glass Work during their three years' course, and to the foremen and workmen who come to the Institut d'Optique. It is rather a book for the master than for the pupil, for certain questions which are treated in it require more elementary lessons adapted to the degree of general education of the pupil. The second part of the work is particularly intended for optical engineers in charge of precision optical workshops." (Free translation.)

An account of the normal procedure in 1920, including details of the manufacture of optical glass, is to be found in *The Manufacture of Optical Glass and of Optical Systems—A Wartime Problem*, by F. E. Wright, published by the Government Printing Office, Washington, U.S.A.

A good book on optics which the practical optician may study with advantage in order to get a good background of optical knowledge on the theoretical side is *Light for Students*, by Edwin Edser (London: Macmillan & Co., 1915). Finally, I would recommend the reader to peruse repeatedly, until he has thoroughly absorbed it, the few pages on optical instruments in the article on optics by Lord Rayleigh in the 9th edition of *Encyclopaedia Britannica*, 1884.

CHAPTER III

THE NATURE OF GRINDING AND POLISHING

§25. The object of polishing is to produce regular transparent surfaces on a piece of glass or other clear substance. The surfaces are usually required to be flat or spherical, although occasionally slight departures from these shapes are needed in order to obtain some optical advantage not otherwise attainable. The process is divided into two, grinding and polishing. They are commonly held to be quite different in character, although this opinion is not universal.

§26. Lord Rayleigh (1903) states that the particles of emery in grinding glasses appear to act by pitting the glasses, *i.e.* by breaking out small fragments. He points out that surfaces may be ground so fine that a candle is seen reflected at an angle of incidence not exceeding 60° and, indeed, that at grazing incidence even coarsely ground surfaces behave as if polished. The wave theory, he says, shows that a regularly corrugated surface behaves as if absolutely plane, provided that the distance apart of the corrugations is less than a wavelength of light.

"In view of these phenomena we recognise that it is something of an accident that polishing processes, as distinct from grinding, are needed at all; and we may be tempted to infer that there is no essential difference between the operations. This appears to have been the opinion of Herschel whom we may regard as one of the first authorities on such a subject. But, although perhaps no sure conclusion can be demonstrated, the balance of evidence appears to point in the opposite direction. It is true that the same powders may be employed in both cases. In one experiment a glass surface was polished with the same emery as had been used effectively a little earlier in the grinding. The difference is in the character of the backing. In grinding the emery is backed by a hard surface, *e.g.* of glass, while during the polishing the powder (mostly rouge in these experiments) is imbedded in a comparatively yielding substance, such as pitch. Under these conditions, which preclude more than a moderate pressure, it seems probable that no pits are formed by the breaking out of fragments, but that the material is worn away (at first, of course, on the eminences) almost molecularly." (*loc. cit.*)

§27. The opinion of Herschel referred to by Lord Rayleigh is from *Enc. Met.*, Art. Light, p. 447, 1849. Herschel says: "... it may reasonably be asked, how any regular reflection can take place on a surface polished by art, when we recollect that the process of polishing is, in fact, nothing more than grinding down large asperities into

smaller ones by the use of hard gritty powders which, whatever degree of mechanical comminution we may give them, are yet vast masses, in comparison with the ultimate molecules of matter, and their action can only be considered as an irregular tearing up by the roots of every projection that may occur in the surface. So that, in fact, a surface artificially polished must bear somewhat of the same kind of relation to the surface of a liquid, or a crystal, that a ploughed field does to the most delicately polished mirror, the work of human hands."

§28. Lord Rayleigh continues: "The progress of the operation is easily watched with a microscope, provided, say, with a $\frac{1}{4}$-inch object glass. The first few minutes suffice to effect a very visible change. Under the microscope it is seen that little facets, parallel to the general plane of the surface, have been formed on all the more prominent eminences. The facets, although at this stage but a very small fraction of the whole area, are adequate to give a sensible specular reflection, even at perpendicular incidence." And further on, "Perhaps the most important fact taught by the microscope is that the polish of individual parts of the surface does not improve in the process. As soon as they can be observed at all, the facets appear absolutely structureless. . . ."

". . . Of course, the mere fact that no structure can be perceived does not of itself prove that pittings may not be taking place of a character too fine to be shown by a particular microscope or by any possible microscope. But so much discontinuity, as compared with the grinding action, has to be admitted in any case, that one is inevitably led to the conclusion that in all probability the operation is a molecular one, and that no coherent fragments containing a large number of molecules are broken out. If this be so, there would be much less difference than Herschel thought between the surfaces of a polished solid and of a liquid."

These passages still refer to polishing by the same emery as was used in the grinding.

§29. The nature of the ground glass surfaces was studied very thoroughly by Preston (1922, 1926). It is not possible after reading his account or the earlier one of French (1916) to think of a ground glass surface as merely a number of intersecting cuts or grooves, a view which was formerly held by some. It is well known that a smooth unbroken line can with care be drawn on glass with a diamond, and I have indeed seen under the microscope what appeared (though broken when observed) to have been originally continuous threads of glass shaved away from the polished surface by a lightly loaded diamond in the ruling of a fine line; but Preston, as a result of a number of careful observations, confirms what Lord Rayleigh says, namely that the process carried out preparatory to polishing the surface produces a great number of conchoidal fractures from which pieces of glass have been

broken. Conditions of stress under which such fractures could originate were studied by Dalladay and myself (Dalladay and Twyman, 1921). Preston also observed another peculiarity of ground surfaces, namely that below the obviously broken surface referred to above, there is a region of small cracks which must be removed by polishing if the surface is to be perfectly clear.

Attempts made by Rayleigh (1908) to discover whether the surface of polished glass is different in physical properties from the mass, resulted in the conclusion that while grease and moisture on the surface (though extremely difficult to avoid) did not have much effect on the optical properties of the surface, yet even a recently polished surface is in a highly complicated condition.

§30. Beilby (1921) brought fresh light on the problem of polish by his observations on metals, glass and Iceland Spar. According to Beilby, in polishing, molecules are set in gliding motion by the polisher so that they form an extremely thin film of fluid subject to surface tension, and this, he thinks, accounts for the smooth surface which is left by polishing.

§31. French (1916–1917) made a number of experiments which led him to the conclusion—to a great extent in harmony with the views of Beilby—that the surface of glass is converted in polishing into a form having properties materially different from the remainder. It can, for example, receive smooth-sided scratches ("sleeks") whereas scratches which are deep (called by the optician "cuts") invariably consist of a series of conchoidal fractures. French actually went so far as to state that he believed the glass to become melted, a view which I, for one, regarded at the time as fantastic. In one illuminating passage (1917, p. 23) he draws a sharp distinction between two stages of wet and of dry polishing, "The function of the first stage is to remove material; the function of the second is to fill up sleeks."

Preston (1926) on the other hand concluded, after a careful examination of the views of previous workers, that the process of polishing is principally one of microscopic abrasion, although "flow or fusion of some sort on a molecular scale may in fact be operative simultaneously with the more important phenomena of mechanical abrasion."

§32. John Strong (1940) describes the polishing operation as a planing process. The grains of abrasive appear, he says, to fix themselves automatically in the soft material of the tool, usually pitch, so that their crystal surfaces are parallel to the direction of motion of the tool and parallel to the plane of its surface. Thus a complex scraper is formed. As this moves over the glass, the height of each abrasive particle is automatically adjusted in the soft backing so that it produces a fine smooth cut. The removed glass is washed away by the liquid lubricant, usually water. The planing action starts on the peaks of the "hills" that result

from the fine grinding and produces a full polish there at the first stroke. Continued operation of the polishing tool removes additional glass, so that the hills become plateaus and are finally planed down to the level of the deepest valleys.

§33. The suggestion of French that the glass actually becomes melted in polishing has recently received remarkable support as a result of experiments by F. P. Bowden and K. E. W. Ridler. Working (1936) at the Laboratory of Physical Chemistry, Cambridge, these authors deduced from their experiments the temperature of the surface layers of bodies during their sliding on one another, by using the rubbing contact of the two substances—actually two different metals—as a thermocouple and determining the electromotive force generated on sliding.

Their experiments show that the local surface temperature as so found is surprisingly high, and could exceed 1000° C. even though the mass of the metal was cool. The behaviour of readily fusible metals confirmed that the temperature measured was a real one, for with metals of low melting point, such as gallium, Wood's metal, or lead, the measured temperature rose to a constant value which could not be exceeded and which corresponded numerically to the melting temperature of each metal.

§34. To this summary of opinions of some of those who have studied the subject, I may add one or two personal observations of my own.

In polishing optical glass it is quite certain that glass is removed. No one who has done any figuring by local retouching will doubt this. In correcting large plates for Michelson echelons I never found that retouching caused any rise of surface in the adjacent area. Thus it is not usually a matter of mere sweeping of the removed glass along the polished surface ; the glass is actually taken up by the polisher or comes way with the rouge.

I used, in retouching, to keep account of the amount of rubbing and the quantity of glass removed. Counting the number of circular sweeps with a $1\frac{1}{4}$ inch diameter cloth polisher with the rouge fairly moist, and taking strokes of about 1 inch in diameter, I found that 100 strokes per inch of the area being polished removed about one Newton's ring (using Michelson's test, §190)—that is about $\frac{1}{150000}$ inch. It follows that a single sweep with such a polisher would remove $\frac{1}{100}$ of this, that is $\frac{1}{15}\times 10^{-6}=7\times 10^{-8}$ in. Now if we consider a molecule of silica to have the dimensions of one lattice spacing of a silica crystal, the size of such a molecule will be about 10^{-7} in. Since one can apparently continue this process of reduction to any extent merely by continuing the rubbing (I have myself carried the process to a depth of about a dozen Newton rings) one can only come to the conclusion that one is removing the glass in portions of less than molecular dimensions, and this is scarcely consistent with the picture of a flowing liquid.

Secondly, although in ordinary figuring the glass is removed, either being carried away with the polisher or becoming mixed with the rouge, yet in certain exceptional circumstances one can get a transfer of the glass of a comparatively massive character, to which no other word seems applicable except "flow". In some small prisms, of which at one time we polished a considerable number, there was an obtuse angle, and if one surface was being polished singly by the optician, occasionally when the rouge was allowed to dry up pretty thoroughly the prism was found suddenly to develop, on the surface not being polished, a small bulge. Speaking from memory, I should say that its height was something like $\frac{1}{4}$ mm. (French, in the paper cited, observed what may have been the same phenomenon, but he found the "lump" to consist of a mixture of rouge and glass.)

These abstracts from the works of Rayleigh, Beilby, French and Preston do scant justice to the originals, which will amply repay careful study ; I must leave it to the reader, after such study, to form his own mental picture of what takes place when glass is polished.

CHAPTER IV

TOOLS AND MATERIALS IN GENERAL USE

§35. The machines in general use (with the exception of those referred to later for the mass production of high quality lenses) are very simple and pretend to no accuracy of construction. The accuracy of the surface to be produced is very high. A piece of plate glass, say 6 in. square, may have inequalities of one-hundredth of an inch; from a number of specimens a piece with errors no more than one-thousandth of an inch may be selected. The surfaces of good spectacle lenses depart from true spheres by amounts of the order of one ten-thousandth of an inch, while the optical work in good binoculars rarely has errors of as much as one hundred-thousandth; and, finally, the best optical work of the few firms of highest repute depart from the ideal aimed at by less than one millionth of an inch. To obtain such precision by nice mechanical guidance of the tool would be a hopeless task, even were the mechanism perfectly rigid, the polishers free from wear or flow, and the films of polishing substances of invariable thickness. None of these conditions are complied with, and the optician relies for the production of accurate polished surfaces on quite other principles than those used by the engineering machinist.

He is satisfied, then, with a machine which will move his polisher to and fro over the surface of his lens or block of lenses from say 6 to 250 times a minute according to the size of the work. Simultaneously the tool, or lens, whichever is undermost, rotates on a vertical spindle, the uppermost element being allowed to rotate freely as it will.

§36. The pitch or other base for polishing material not being a true solid, but a liquid which, though rigidly resisting distortion in passing over any small inequality of surface, yet, by a slow accommodation to the surface (spherical in the main) over which it passes, retains a spherical shape whose radius of curvature is always that of the surface it is polishing. It may be here mentioned that, as the polishing proceeds, there should—if it is desired that the grey should be uniformly removed (and this is the ideal which makes for quickest polishing) be a commensurate (small) variation of the radius of curvature of the polisher; and this actually occurs in practice by amounts which are quite measurable where the radius of curvature is small.

§37. Trueing Tools

The material most in favour for use for optical tools for trueing, smoothing and forming the polishers, is cast iron. We find the most satisfactory type to be Meehanite, an iron in whose preparation the

molten metal has been treated with calcium silicide, which acts as a graphitizer and also gives a fine graphitic structure. This form of iron casts very free from blow holes or other defects. Curved tools for lenses are turned to the required radius and must then be ground together until they exactly fit. Since the turning process is enormously quicker than grinding there is an economy of time in producing as fine and accurately turned surface as possible, or better still the surface may be ground to shape on a circular grinding machine. Such curved tools should be ground together with trueing emery (see §62) although here again time may be saved by rubbing them together with the trueing emery and then rubbing down the places of contact with a piece of lead held in the hand, feeding in the coarser emery or carborundum, the tool being rotated on a vertical spindle. The final rubbing must be done with trueing emery and must be carried on until, when the emery is wiped away and the tools are rubbed together, they touch over nearly the whole surface, a condition which can be appreciated either by the fact that there is no tendency for them to bind on the outside or to swing around the centre, or alternatively that when rubbed together vigorously a few times and then examined, neither the middle nor the outer margin should be especially bright except in the case of the tools of shorter radii (see §105). The tools must then be measured with a spherometer in order to ascertain whether the radius is actually near enough to that intended.

§38. The Spherometer

This consists of a metal triangular frame, with three pointed legs fixed at the corners of an equilateral triangle. Equidistant from these legs is a pointed micrometer screw with divided head and scale. When the central screw is raised high enough the three legs stand firmly on the optical tool or other surface, the radius of curvature of which is to be measured. When, however, the central point is screwed down to touch the surface, the instrument swings freely about the point of contact. The instrument is set for zero by placing it on a flat optical tool or preferably a proof plane. The radius of curvature is given by the formula

$$r = \frac{s^2}{2d} \times \frac{d}{2},$$

where s is the distance from the point of the micrometer screw to the points of each of the three legs when adjustment is made on a flat surface and d is the distance which the micrometer screw must be raised or lowered to be adjusted to the surface under test.

§39. When I used spherometers of this type forty years ago I found it extremely difficult to ascertain what was the effective radius from the centre of the point of contact to the lens. I therefore had a ring form

made (Fig. 2), the ring being so ground as to have two truly circular, sharp edges, one of which makes contact with concave and the other with convex surfaces. It is a severe test for a spherometer if, when two optical tools of fairly short radius and, say, about three times the diameter of the spherometer, carefully ground to be in contact, yield the same measurement of radius. The inside and outside diameters of my spherometer can be accurately measured in spite of the simplicity of the instrument. With this simple ring form a closer agreement can be found than with the three-legged form.

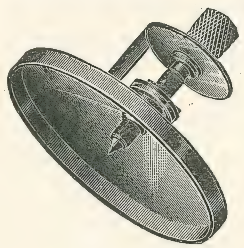


FIG. 2.
Ring-form Spherometer.

The original ring-form spherometer has been in use in our optical testing room for over thirty years, and is still in good condition.

§40. The Guild Spherometer is a robust and accurate instrument but is only suitable for use with transparent test objects such as lenses or proof plates.

The Guild Spherometer is, in principle, similar to the older form of spherometer having three legs or a circular ring with a centrally mounted adjustable micrometer screw, but differs from that form in that it aims at the elimination of the principal source of error, viz., the inaccuracy in the determination of the exact point of contact of the micrometer screw with the surface under examination.

Fig. 3 gives a general view of the spherometer. The test surface is rested upon a support consisting of three small steel spheres of the same radius, or alternatively, a steel ring may be supplied for this purpose. A small quartz sphere is attached concentrically to the end of a micrometer screw of high accuracy and is adjusted by rotation of the divided drum, to make contact with the surface under test. By means of a microscope provided with a vertical illuminator, the system of Newton's interference rings formed between the test surface and the quartz sphere may be closely observed through the object under test in order to determine the exact moment of " contact ", by which is meant in practice the position where some definite and easily recognisable configuration of the interference pattern occurs. Settings may in this way be made under conditions capable of control and repetition to an accuracy measured in fractions of a wavelength of light, thus ensuring that the utmost advantage is taken of the high degree of mechanical perfection of the instrument.

The ball or ring supports are removable and accurately replaceable. For use in measuring curvatures of surfaces of varying diameters, four sizes of such rings or of ball supports are supplied with each instrument,

of the following diameters—12·5 mm., 25·0 mm., 37·5 mm., and 50·0 mm. for metric micrometers, and corresponding dimensions for English micrometers.

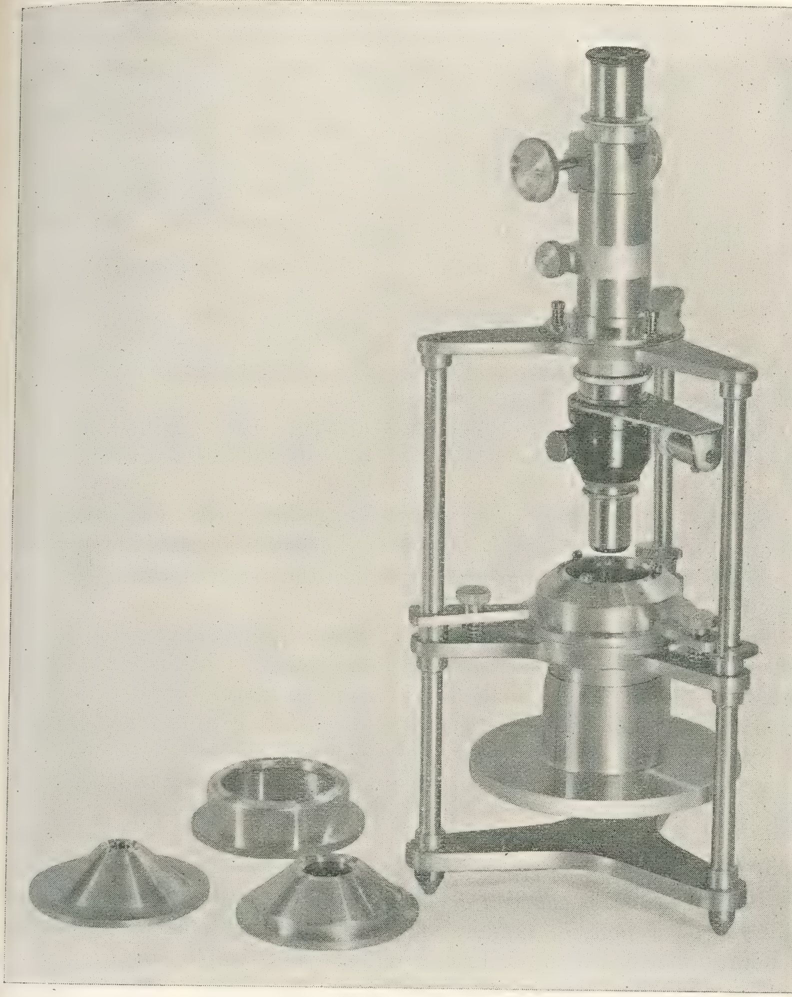


FIG. 3. The Guild Spherometer.

§41. In making a measurement with the Guild Spherometer the procedure followed is as with the three-leg spherometers of the older type. A setting is made upon an optical flat and, following that, upon the spherical surface to be measured for radius, using for this purpose as

large a support for the surface as possible. If, then, the difference between the zero reading obtained for the optical flat and the reading for the surface under test be h, the radius of the surface is given by

$$r=\frac{A}{h}+\frac{h}{2}\pm a$$

where the sign − for the last term applies to convex surfaces, and the sign + to concave. The constant a is the radius of the steel balls, and is omitted from the formula when the ring supports are used. The constant A is given by $A=\frac{1}{2}R^2$, R here being the radius of the circle of contact with the steel ring, or the radius of the circle circumscribed about the triangle formed by the centres of the three balls. The radius R in this case is given by

$$R=\frac{\alpha\beta\gamma}{4\sqrt{s(s-\alpha)(s-\beta)(s-\gamma)}}$$

α, β and γ being the distances between the ball centres, found by means of a hand micrometer, and $s=\frac{1}{2}(\alpha+\beta+\gamma)$.

The formula given above for r is also used when making measurements with the simple ring or three-leg spherometer, the constant α then being omitted.

§42. We will assume, then, that by measuring the tools with the spherometer, grinding them locally with the lead lap, and rubbing them together, they have at length been made of the correct radius of curvature.

The two tools so prepared are the " true " or finishing tools and in polishing blocks of lenses two others are required, a block holder and a polisher holder. These must be of radii respectively greater and less than the radius of the tool when a convex surface is to be polished, and vice versa when the surface to be polished is concave (see Fig. 18). This variation of radii only becomes important with the shorter radii, say with a 9 in. diameter tool for radii of curvature less than 12 in.

§43. Flat Tools

A set of flat tools consists of four ; three of them are finishing tools and one is a polisher holder. In flattening the tools the principle generally attributed to Sir Joseph Whitworth is employed.

" In 1840 he attended the meeting of the British Association at Glasgow, and read a paper on the preparation and value of true planes, describing the method which he had successfully used for making them when at Maudslay's, and which depended on the principle that if any two of three surfaces exactly fit each other, all three must be true planes. The accuracy of workmanship thus indicated was far ahead of what was contemplated at the time as possible in mechanical engineering. . . . "

(From *Encyclopaedia Britannica*, 11th edn., vol. 28, p. 616.) See §159 for method of determining the flatness of tools. Three diameters of tools are found to be convenient, 9 in., 11 in. and 13 in. The cross-section is shown in Fig. 13.

The tools of 13 in. diameter of cast iron are rather heavy for handling by most women or quite young lads. In such cases, therefore, for the polisher holders aluminium is desirable, although it is not suitable for trueing, smoothing or forming the polishers. It does not appear that polishers built up on aluminium tools act any differently from those built up on iron ones.

The abrasives used are dealt with in §60 *et seq.*

POLISHERS

§44. Pitch Polishers

The function of the polisher is to provide an accurately shaped flat or spherical medium for applying the polishing material.

§45. The polisher holders (convex and concave) are similar to the trueing tools, but if deep (say of a radius of curvature less than twice their diameter) should be of a radius of curvature greater or less than that of the trueing tool (according as the latter is convex or concave) by such an amount that the polisher is of a uniform thickness.

§46. Polishers are usually of pitch although felt or cloth is sometimes used for the commoner work. Various wax mixtures are also used, but they polish more slowly. For pitch polishers the writer's experience is that there is nothing better than wood pitch (Swedish) filtered when hot through chiffon (100 mesh to the inch) and then boiled until, at the temperature at which it is to be used, it can be indented readily but not deeply by pressure of the thumbnail. Although this rough test is often the only one applied, it is the better practice to use a mechanical device applied for a definite time and to measure the indentation produced by it. Such a device will be described later (§48).

§47. Dealing first with polishers made of pitch, the properties to be desired are to a certain extent contradictory in nature. In the first place the polisher must be susceptible of a certain amount of flow so that it can be formed by application of the flat or curved tool to give it the right shape. The rate of flow must, however, be slow so that the surface which has been imposed on it will in turn be imposed by it on the glass surfaces which are to be polished. If it is too soft it will rapidly go out of shape during the polishing process, and thus frequently require re-forming. This re-forming takes time, although it is not necessary to heat the polisher for this purpose ; it suffices to warm the forming tool slightly, or it may even be used cold. If the viscosity is too high, dust falling on the polisher will cause scratches before sinking into the surface of the polisher and thus becoming innocuous.

§48. It will be gathered that the mobility, or its reciprocal, the viscosity, of the polishing medium is a very important property (mobility = 1/viscosity). In order to acquire the right degree of viscosity, then, the filtered pitch is boiled in a cauldron and from time to time a small piece is submitted to test in a simple, but quite satisfactory viscosity measurer. This (Fig. 4) consists of a piece of steel $\frac{1}{4}$ in. diameter, with a truncated conical point of 14° included angle, terminating in a $\frac{1}{2}$ mm. diameter flattened point. Attached to this is a weight. The rod with its weight is held loosely in a vertical position by the top of the rod passing through an eyelet in a wooden upright which itself is supported on a flat wooden stand and has a total weight of 1 kg. The point of the rod is allowed to bear on the top of the pitch, or other substance whose viscosity it is desired to control, which is immersed in water and thus kept at any desired temperature. The length of time taken for the rod to fall a given distance is determined.

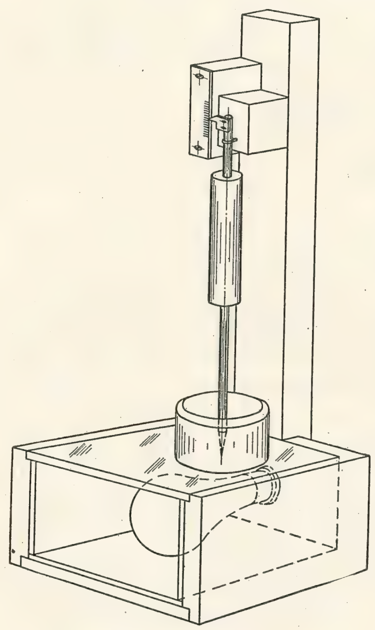


FIG. 4.
Pitch Viscosity Testing Apparatus.

A regulation established in our workshops (but persistently varied at the will of the skilled men within narrow limits according to their individual tastes) states that pitch is to be prepared and stocked for polishers in two degrees of viscosity. On the first the standard jig falls $1\frac{1}{2}$ mm. in five minutes ; on the other the standard jig falls 3 mm. in the same time, the temperature in each case being 70° F. Should the pitch be inadvertently made too hard by boiling, it may be softened with gas tar.

§49. A satisfactory substitute for wood pitch is gas pitch, obtainable from the Tar and Ammonia Products Works, The Gas Light & Coke Co., Beckton, East Ham, London, E. 6. If the order specifies to them that the pitch should be "60° C. K. & S. Grade" (as supplied to Adam Hilger, Ltd.) it will be about our $1\frac{1}{2}$ mm. standard viscosity. (See above.)

§50. Owing to the rapid change of the viscosity of pitch with temperature (it is halved for each $1\frac{3}{4}$° C. rise of temperature), a given pitch

will only be at its best as a polisher over a range of $\pm 7\frac{1}{2}$° F., say ± 4° C. The thickness of the polisher should be about $\frac{1}{4}$ inch.

§51. During the Great War of 1914–1918 when we trained many women to do glass polishing, we carried to extremes the attempt to remove foreign matter, in the hope that by so doing we could remove the tendency to scratches which is one of the main faults which occur in the polishing of glass by unskilled workers. With this aim we filtered the pitch through filter paper in an oven at from 200° to 300° C., while the air was fed into the workshop through a chamber screened by two separated filters of fine chiffon (100 mesh per inch).

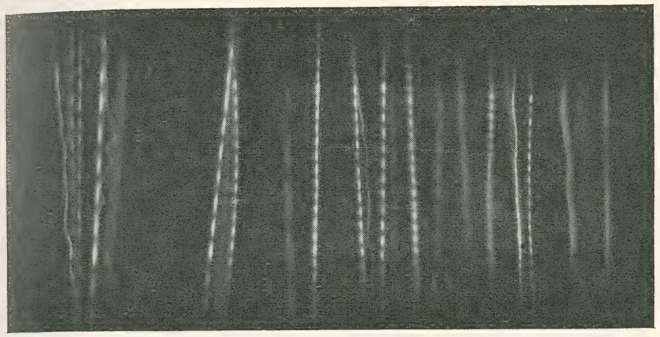


FIG. 5. Fall of dust particles.

Several years experience with this technique left us with the belief that little advantage was derived from this extreme caution. Scratches are not chiefly due to foreign matter in the pitch, but to dust (chiefly siliceous in nature) which falls on the polisher. Meticulous care to avoid this is not so important as to ensure that the pitch is so soft that such particles sink into the polisher rather than scratch the glass, or at worst cause the kind of light scratches known as "sleeks" which are distinguished by an abrupt and relatively severe head at one end, tailing away to invisibility at the other.

We are now satisfied to use as the chief protection against injurious dust a screen, some six feet or so above the polishing machines, consisting of sheets of "Windolite" (non-inflammable transparent glass substitute) supported on chicken wire ; the worst dust is heavy and the screen is a very useful protection against this. One must not suppose, however, that such a screen is a complete protection against fine dust being carried over the polisher. Experiments have been made in our laboratory on the rate of fall of emery and we find that it is far less than the speed of the air currents which are present in the air of a workshop under ordinary working conditions. The method of experiment was to illuminate the air in which the dust was moving with a powerful beam

of light and to photograph the falling particles against a dark background. The source of illumination was an A.C. Mercury vapour lamp, so that the light was intermittent with a frequency of approximately 100 flashes per second. Thus each falling particle appeared as a dotted line in which the separation of the dots was the measure of the speed. A specimen photograph enlarged about six times is shown in Fig. 5. The following results were obtained :

Material.	Diameter (average) in 0·01 mm.	Rate of fall in mm. per sec.
Lycopodium powder	—	28
Emery	1·0	31
,,	2·5	36
,,	·7	30
,,	5·0	62
Carborundum	18	125
,,	x80	25

The above photographs were taken in an enclosed chamber. Measurements were then taken of the movement of the particles under various working conditions, using as a test powder lycopodium powder. Photographs were taken with the machines still, with the machines running, and shortly after the door of the workshop was slammed. The chief source of draughts under ordinary working conditions seems to be the revolving of the machine belts, but the currents of air caused by the slamming of the door were much greater. The measurements were taken over the machine which is provided with a canopy. They were then repeated with the addition of screening at the sides and back of the machine and this was found very effective in reducing the tendency for the dust to be carried in over the polishers. The machine was a 6-spindle polishing machine taking 13 in. tools. The following is a summary of the results :

Conditions.	Movement without screen. Angle to horizontal.	Speed mm. per sec.	Movement with screen. Angle to horizontal.	Speed mm. per sec.
Machine stopped	50°	167	70°	42
Machine running	30°	100	60°	63
After slamming door	20°	200	45°	83

Although the emery of 1·0 grain of which the photograph was taken was what we should regard as well-graded it will be noted that a great variety of grains are present, including some extremely small. It would appear that a very refined method of grading the finer grains might be derived from these results—a uniform horizontal current of air distributing the grains according to their size in receptacles placed in line below a thin stream of the falling powder.

Anyone designing a new optical workshop should adopt the measures recommended in §126.

§52. Many skilled workers add various ingredients to the pitch ; for example I find in my notes of 1915 that at that time an approved mixture was pitch—8 parts, rosin—1 part, beeswax—1 part ; later on pitch—10 parts, rosin—1 part, beeswax—$\frac{1}{2}$ part was preferred. However, as time went on I was unable to find any strong consensus of opinion as to the purpose served by such additions, although it is stated, and seems reasonable, that the addition of beeswax reduces the tendency to scratch. The general routine in our workshops is now to use pure Swedish pitch, of standardised viscosity. If wood pitch is not available, a satisfactory substitute can be made by softening gas pitch with creosote.

§53. Wax Polishers

For a considerable amount of work done by unskilled workers in our workshops during the Great War of 1914–18 wax polishers were employed. A great variety of mixtures was tried, for example—Beeswax $3\frac{1}{2}$ lb., black rosin 2 lb., is noted by me as exceptionally good for avoiding scratches. One competent foreman after much experience with polishers of this character prepared—Beeswax $3\frac{1}{2}$ lb., black rosin 2 lb., pitch $\frac{1}{4}$ lb., and tallow " a small quantity ".

There is no doubt that such polishers are far less liable to cause scratches and sleeks than are pitch polishers. They are, however, difficult to make flat. Wax mixtures such as those mentioned do not flow to the same extent that pitch does and they can only be flattened by scraping, at least until the stage is reached when almost the whole surface has been in this way made to fit the forming tool very closely. If from this stage onwards the tool is rubbed on the polisher with the customary rouge paste, eventually a satisfactory flat polisher is formed which will do excellent work and keep its shape very stubbornly.

Wax polishers polish more slowly than pitch and do not so readily produce accurate surfaces.

§54. The difference of behaviour of pitch and wax as regards flow may be very simply demonstrated in the following way. If a ball of pitch such as is used for polishers, and one of wax mixture consisting of beeswax and resin in equal proportions, are placed under equal weights and left for a week, the pitch will become entirely flattened, while the wax will remain unchanged in shape.

The relative liability of pitch and wax polishers to cause scratches may be illustrated as follows. If two small flat polishers, one of pitch and one of wax, are placed on a piece of glass with a few grains of carborundum between the glass and polishers and the polishers are allowed to rest ten seconds and then pushed along the glass plate for an inch or

two, one can distinctly feel and hear the carborundum under the pitch polisher scratch the glass, whereas the wax polisher moves smoothly and without sound over the glass. On examining the glass it is found that where the pitch polisher has passed there are numerous severe scratches, whereas the wax produces only extremely faint ones.

§55. Another typical polishing wax is made by mixing equal parts of beeswax and putty powder: another which though slow is very "fool-proof" is made by mixing three parts of rouge with four parts of paraffin wax. Although the writer has tried a great number of variants of the above materials for polishers obtained by various mixtures of pitch, beeswax, paraffin wax, rosin, putty powder, rouge, willow sawdust and other materials, he has never been able to establish any certain superiority of any of them over the simpler ones already mentioned. Polishing materials are dealt with in §65 *et seq.*

§56. Mallet Pitch

If a number of lenses are to be polished together they are held on a tool similar to the trueing tool by blobs of cement known as mallets, and as with the polisher holder (§45) the radius of curvature should be such that all the mallets are of equal thickness.

"Mallet" is the name given to the pad of adhesive by means of which a lens is affixed to the blockholder for the purpose of polishing a number of lenses at a time. The name is not in general use and seems to have been derived from misapplication of the French "molette", the word used by Cherubin d'Orlèans (see §8) to describe the metal holders for lenses. Mallet pitch should be less viscous than polishing pitch but not too much so; otherwise the simple method described in §91 for setting the lenses truly in the block would not be feasible.

§57. The mixture which I approve as standard practice is one on which the standard viscosity measuring jig (see §48) falls not less than $\frac{1}{2}$ mm. nor more than 1 mm. in five minutes at the temperature of the shop in which it is to be used, at which temperature it is suitable for use.

At 58° F. this is given by 5 lb. of pitch (4 mm. at 70° F., see §48) and 8 lb. of red ochre. This is suitable for use for blocks of large-diameter lenses whose polishing is carried out at a slowish rate. If the lenses are of small diameter and the polishing is quick so that more heat is generated, a stiffer mallet mixture may be used in which the fall of the standard jig is only $\frac{1}{4}$ mm. instead of $\frac{1}{2}$ mm. This is attained by the use of 7 lb. of yellow ochre instead of the 8 lb. of red ochre. Mallet pitch is only fully satisfactory when it is used over a rather narrow range of temperature, say $\pm 7\frac{1}{2}$° F. (± 4° C.).

§58. If the lenses are thin the $\frac{1}{2}$ mm. mallets are liable to distort the lenses, so that they are a bad shape when released from the mallets; the remedy is then to use a softer mallet (up to $2\frac{1}{2}$ mm.). The softening

can be effected by adding more pitch. If the block polishes unevenly due to the lenses sinking, the worker must use his observation to ascertain the best hardness for the particular job he is doing, steering a middle course between the hardness which causes distortion, and the softness that causes sinking.

§59. Where a large number of the same kind of lenses is being made specimens of mallet pitch should be taken from the cauldron every day (after vigorous stirring), tested for hardness, and the mixture hardened or softened to the degree experience has shown to yield the best result. Vigorous stirring is essential as the red ochre tends to sink to the bottom of the cauldron.

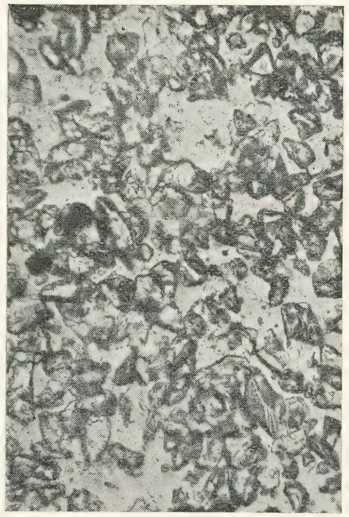
§60. Abrasives

For roughing, the fastest material is carborundum; for trueing and smoothing various forms of aluminium oxide (Al_2O_3) are used. The impure natural forms known as emery have been used for grinding from time immemorial, and up till the end of the nineteenth century the emery from the Isle of Naxos had formed the principal source of supply for the optical industry. Purer and quicker cutting natural forms known as corundum are found in the United States of America, Canada, Madagascar, and elsewhere. We have used Naxos, Madagascar and Canadian corundums, and found the Canadian distinctly the best of the three, while the artificial forms sold under various names (aloxite, alundum, etc.) are better still. It is stated in Strong's book that the natural forms of corundum cut more quickly than the artificial types. This is not in accordance with our experience. The artificial corundum known as aloxite we find to be quicker than Naxos, Canadian or Madagascar corundum. All those mentioned require grinding and grading by elutriation; a very fine and uniformly graded material being of the highest importance if speedy polishing is to be attained.

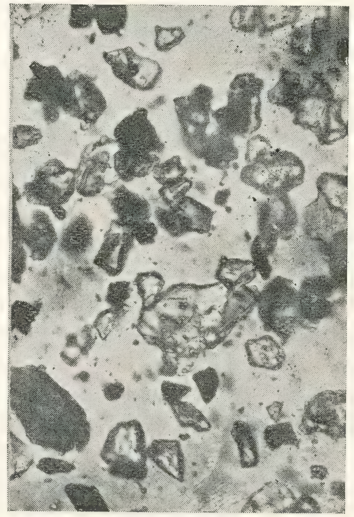
§61. The usual nomenclature used to distinguish the emeries of different grades is to name them 1 minute, 2 minutes, 40 minutes, 60 minutes, up to 240 minutes (although emeries of more than 120 minutes are very little used). These designations indicate the duration of the decantation by means of which they have been selected by the following process. (Freely translated from Dévé (1936), pp. 34-36):

"The process of grading is known as elutriation and is based on the time occupied by the grains in passing through a vessel of water 1 metre high and about 30 cm. in diameter. The weight which causes the fall of a particular grain is proportional to its volume, that is to say to the cube of its dimensions. The force which resists that fall through the water is mainly a force of fluid friction proportional to the area, that is to say to the square of its dimensions. If then one doubles the linear dimensions the volume is multiplied by 8 and the surface by 4. If we

imagine 8 little cubes of 1 mm. side they will weigh as much as a single cube of the same material of 2 mm. side. The surface of such a little

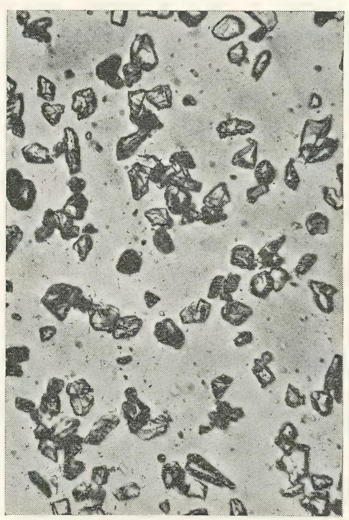


November 1914.

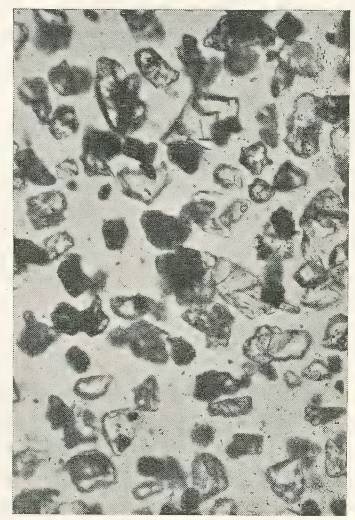


July 1916.

(6)



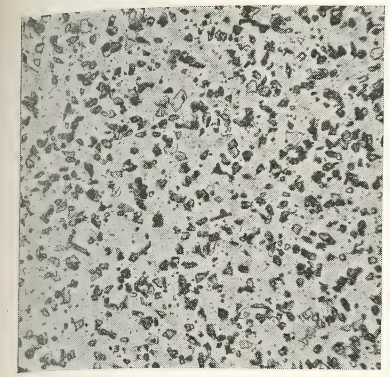
November 1914.



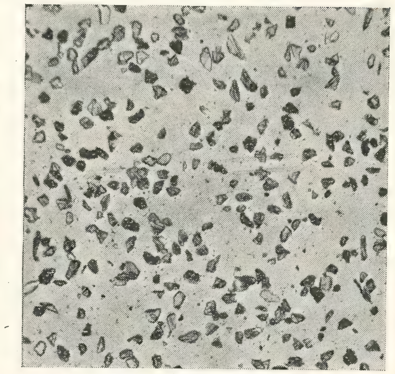
July 1916.

(7)

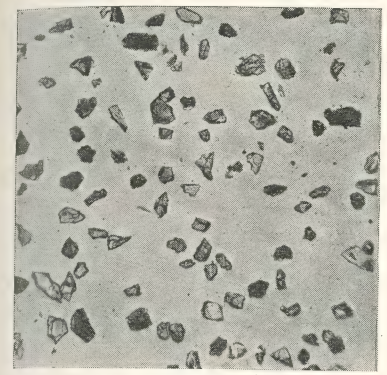
FIGS. 6 and 7. Microphotographs of commercial abrasives in 1914 and 1916. (Magnification $\times 370$.)



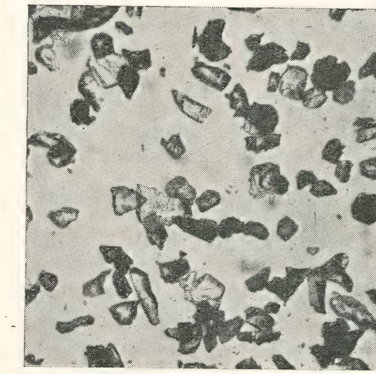
Fine smoothing *B*.



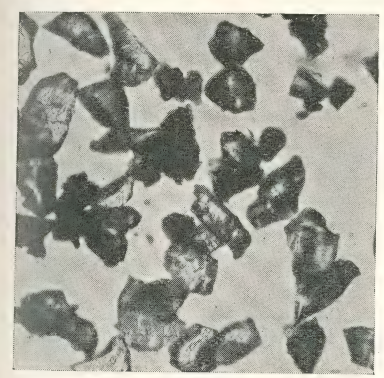
Fine smoothing *A*.



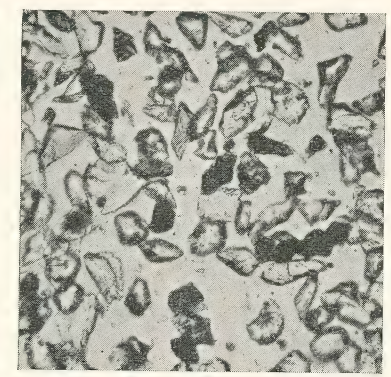
Smoothing.



Extra fine trueing.



Fine trueing.



Trueing.

FIG. 8. Microphotographs of Graded Abrasives. (Magnification $\times 100$.)

cube will be 6 sq. mm. whence the 8 small cubes will together have an area of 48 sq. mm. while the surface of the large cube will be 24 sq. mm.; thus when the large cube and the 8 little ones which weigh together as much as the large one are thrown into the water together, the force which restricts the fall of the little cubes is double that for the large cube which will therefore arrive at the bottom well before the little ones. The procedure, then, is that after the emeries are crushed the mixture of grains of various sizes of about 10 litres volume is put into the vessel, which is then filled with water. One then stirs up emeries of all kinds thoroughly from the bottom of the vessel with a forked tool. Water is then added to make it overflow and carry out all the floating impurities. One then lets the vessel rest for two hours, at the end of which time the water will only contain the finer grains of emery. The water with the floating emery is decanted by a tap half-way up the vessel or by a syphon, and the water thus drawn off together with the floating grains is emptied into another well-polished and very clean vessel where one lets it remain for several days. At the end of that time one throws away the water and dries the deposit, which is the 120 minute emery. The process of stirring, filling up and decanting is repeated after one hour, the resulting emery being then called 60 minute emery."

§62. The Hilger Classification of Emeries

Until early in 1916 we were content to purchase our abrasives since they were found to be sufficiently well graded. Between November 1914 and July 1916, however, grave deteriorations began to take place in the purchased abrasives. Fig. 6 shows under a magnification of $\times 370$ fine abrasives bought under the same designation and from the same supplier in November 1914 and July 1916 respectively; fig. 7 exhibits a like comparison for an abrasive of finer grain. The progress of work in our optical shops was so much slowed up by this deterioration that the output was certainly halved. We therefore made a systematic study of the size of grains of various emeries, and decided to use the phrase "size of grain" as meaning the average diameter of grain in hundredths of a millimetre. It may seem hopeless at first sight to decide what the average size may be of grains which vary so much in shape and size in a single specimen. One finds, however, that an observer comes to much the same conclusion on examining a specimen under the microscope on different occasions, even with carborundum, the grains of which are usually long compared with their width. By size one understands here the diameter of a grain if its bulk were reduced to a sphere. Even when the observation is made by different people the method of simple observation under the microscope enables us to class the fineness of a given sample of emery in a way which meets with the agreement of the skilled workmen who use them. The next step

was to define the size of grain, and a number of experiments showed that the following formed a complete and useful series:

Operation.	Kind.	Size of Grain. $\frac{1}{100}$ mms
Roughing	Carborundum	40
Fine roughing	,,	20
Trueing	Corundum	10
Fine trueing	,,	5
Smoothing	,,	2·5
Fine smoothing	,,	1·25
Final smoothing	,,	0·6

A sufficiently comprehensive series would be provided by:

Roughing singly - - - -	Carborundum	40
Fine roughing singly - - -	,,	20
Trueing singly - - - -	Corundum	10
Trueing, one emery in the block -	,,	10
Smoothing in the block - - -	,,	2·5
Fine smoothing in the block - -	,,	1·25

It is interesting to compare these with the figures given by Dévé for the average diameter of grains as bought under the classification of "minutes" (§61).

Copied from p. 82 of Dévé (1936):

		Specimens bought in London, 1942
Emeri No. 1 (fin) - -	0·170 mm.	
,, 3 minutes - -	0·112 ,,	
,, 5 ,, - -	0·068 ,,	
,, 10 ,, - -	0·048 ,,	
,, 20 ,, - -	0·042 ,,	0·030 mm.
,, 30 ,, - -	0·038 ,,	0·018 ,,
,, 60 ,, - -	0·022 ,,	0·006 ,,

In the third column I give the measurements of emeries bought from T. A. Hutchison, London, in May 1942, under the designation mentioned in column 1.

The third factor, and a very important one, is the quality of grading, which we define in the following way. Let $D_{\max}$ be the diameter of the biggest grains (excepting monstrosities) and D_{av} that of the average grains, then imperfection of grading is defined as—

$$10\ \{(D_{\max} - D_{\mathrm{av}})/D_{\mathrm{av}}\}.$$

Here again the observer will at first be confused and undecided as to what he should consider a "monstrosity". By this one means an exceptionally large grain present in such small numbers (a single specimen, for example) that it may be regarded as an accidental inclusion and not representative of the bulk. Obviously, if in a small

sample more than one such occurs, the consignment is fitter for rejection than for grading. Perfectly graded material would therefore be marked 0 and less perfectly graded 1, 2, 3, and so on. Experience shows that an abrasive marked 4 or less is good ; one marked 10 would be considered badly graded and is found to be gritty and scratchy in use. Having found by about the middle of 1916 that it was impossible to buy good and well-graded emery from any of the various available sources, we built our own elutriating plant.

§63. We bought aloxite, ground it in a ball mill and found that the resulting mass contained grains of all useful sizes. This was elutriated in an apparatus similar in principle to what is used by geologists in grading soils, etc., and the resulting abrasives were of a better quality than we have ever been able to purchase before or since.

§64. In 1923, however, a further form of Al_2O_3 (Sira abrasive) of great purity, hardness and uniformity of grading became available. It is sold by the United Kingdom Optical Co., Mill Hill, London. Owing to its sharp crystal edges, and to the fact that they maintain their quick-cutting properties, grinding with Sira abrasive is a rapid process. This abrasive is not so fine in grain as the finest of those graded by us, but on account of its uniformity and because of the shape of its grains, it gives a ground surface with shallow pits of even depth.

Since the coarser grades of emery on the market became much improved in quality, we were glad to avail ourselves of the space which had been occupied by our elutriating plant for other purposes. Some of our workmen, however, still treasure minute quantities of the finest of our aloxite abrasive of a grain size about 0·8, and for special work prefer it to anything else which is available.

An interesting table by G. Ritchey, cited by Dévé, p. 77, gives the pressure recommended as the best for the use of various emeries.

Pressure in grams per cm.^2

Emery.	Best Pressure according to Ritchey.	Note by Dévé.
12 to 20 min.	15 g.	to 150 g. for spectacle work.
30 to 60 min.	10 g.	
120 to 140 min. and pitch polishing.	6 g. for large tools. 9 g. for small tools.	For surfaces of high precision.
Paper Polishing	—	30 g. (to 45 g.).
Cloth Polishing	—	50 g. (to 500 g. for spectacle work).
Polishing on waxed cloth	—	25 g.

§65. Polishing Materials

There are two materials in general use for polishing lenses. These are rouge and putty powder.

Rouge is a red oxide of iron (ferric oxide), Fe_2O_3, usually prepared in a fine state of division by calcination of ferrous sulphate. The best rouge for lens polishing should have a good red colour and should contain little or no free sulphate. Excess of sulphate is detrimental to good polishing as it causes the powder to aggregate in balls and thus gives rise to sleeks in the polished surfaces. It is also likely to cause enamelling, which is sometimes difficult to remove in the final stages of polishing. A light-red coloured, very fine-grained rouge generally implies that the calcination has not been complete or that the temperature of heating is too low. Such a rouge will usually have a high sulphate content. On the other hand, if the rouge has a very dark brown or purplish colour it indicates that the temperature of calcination has been too high, and a rouge of this colour will be too hard and gritty for successful lens polishing. (A rouge manufactured by Messrs. Hopkins & Williams, Ltd., to the specification of the British Scientific Instrument Research Association and called " Sira " rouge has been specially prepared for the best optical work. It is a fine, uniformly grained powder and is free from any trace of sulphate.) To get the rouge in the form of a water paste in which it is suitable for use, it is mixed in a jar with about three times its bulk of water, allowed to stand for twenty seconds and the top poured off into a second clean jar. The grit and coarse particles, if any, will remain behind in the first jar. When all the rouge has settled in this second jar, the surplus water is carefully poured off. The remaining rouge paste is then ready for use and will remain so as long as it is not allowed to dry. This is suitable for pitch polishers. For cloth polishers a little fuller's earth (one-twelfth part) may be added to the rouge. Dévé states that extra-fine polishing rouge has a grain of 0·003 mm. to 0·006 mm., while Tripoli powder for polishing on paper gives 0·002 mm. to 0·003 mm.

The second polishing powder in extensive use is putty powder (tin oxide), which is often used with polishers of the wax class and particularly for polishing soft materials. Other substances, such as diamantine and chromium oxide, are of occasional use for special purposes. All these are used wet and in a similar way to rouge.

Note.—In Great Britain putty powder and chromium oxide are only permitted to be used in factories provided the regulations of exhaust ventilation and protective clothing and washing facilities are carried out.

CLEANING LIQUIDS

§66. The following cleaning liquids are found useful in the optical workshop, in addition, of course, to water for such substances as are

soluble therein, such as glue and the so-called "gums" sold as adhesives.

For Shellac, Canada Balsam, de Khotinski cement ("Coates"), black wax, sealing wax, and many varnishes (dull black and others):

Methylated Spirits
Alcohol.

For Pitch, Rosin, Beeswax, Tallow and mixtures of the same, some dull blacks:

Benzene
Turpentine
Turpsad
Petrol
Paraffin.

For Metals:

Nitric Acid
Aqua regia
Strong sulphuric acid with chromic acid added
Potassium cyanide (highly toxic).

The addition of a drop of nitric acid will often assist cleaning with other liquids. For example, the optical contacting of surfaces is difficult even when the surfaces appear quite clean; it may be successfully accomplished, however, if the surfaces are lightly wiped with cotton wool dipped in dilute nitric acid or ammonia, and then washed off with water, finishing with ammonia, wiping the latter off with an old linen handkerchief which has been boiled in distilled water.

Moisture condensed from breath is a useful cleaning medium, and distilled water is better than tap water.

Any rag or linen used for cleaning must itself be scrupulously clean in order to avoid depositing on the glass surfaces any substances dissolved by the cleaning fluids from the cloth. Excessive rubbing should be avoided as the electric charge produced tends to collect fluff on the surface of the glass.

Carbon tetrachloride is a volatile, non-inflammable and very powerful solvent for waxes (including paraffin wax), but a good ventilation for carrying away the vapour is obligatory (Section 47 of the Factory Act). Carbon tetrachloride is rather less toxic than chloroform. The use of tetrachlorethane, also a powerful solvent, is now considerably restricted owing to its strong narcotic and poisonous action, which causes jaundice, fatty degeneration of the organs, albuminuria and haemoglobinuria.

CHAPTER V

PRODUCTION OF LENSES AND PRISMS IN QUANTITY

§67. Single Working and Block Working

The skilled optician should be practised in producing single prisms of high quality, a process which, like glass blowing, although very simple requires much skill and experience. The elements of the process have already been described. The prism may be sawn from a thick block of glass on the slitting machine, roughed and trued in the manner described for lenses in §§17 to 21, attention being given to the points mentioned in §§77 to 79.

In the roughing and trueing processes the prism is made to the correct angles by pressing more heavily on one side than the other, trying the angle at frequent intervals with a square or other angle gauge, or protractor. In the later stages of trueing to angle the Angle Dekkor (§182) is a great help, reflection being obtained by a small piece of plane parallel glass made to adhere to the trued surface by breathing on the latter before putting them together.

Making the polisher is described in §§83 to 87 and a few brief hints on the difficulties of polishing flat surfaces singly will be found in §95.

The great bulk of manufacturing work, however, consists of making numbers of prisms and lenses all of the same size and shape.

In the mass production of lenses, polishing processes have developed in two directions. The first aims at increasing the number of polishing spindles which can be attended to by a single workman. For instance, if the rouge applied to the polisher is very wet, and ample in quantity, then although the polishing process is slower, yet the block of lenses can run for a long while without the polisher drying or overheating. Thus, in the polishing of spectacle and other cheap lenses a single operator can control a hundred or so spindles, dipping a large whitewashing brush into a pailful of the wet rouge and flicking it generously and without undue discrimination over a gang of polishing spindles in rows arranged in tiers one above the other. In the second, in use in other factories, particularly in some making large numbers of lenses (such as camera lenses) of good quality, carefully designed machines are used to secure that the best conditions for good polishing are automatically maintained. For instance, in Taylor's polishing machines (W. Taylor 1918) the rising and falling motion of the member which actuates the polisher is eliminated, and reactions, due to inertia, which are a cause of the polisher becoming deformed, are thus abolished. At the same time the liquid is automatically applied to the polisher when the adhesion between the work

and the polisher increases owing to the drying of the latter (W. Taylor 1922). Similar machines are used for lens smoothing.

In the roughing of glass to shape, a departure from the traditional processes was made by Carl Zeiss Ltd. by the use of copper laps charged with diamond dust and rotating at high speed (1500 revs. or more per minute) with an ample supply of lubricant. This process is described in §71.

Somewhat similar processes have been developed and extended by Taylor to the accurate shaping of lenses, using bonded abrasive wheels. A lens-forming machine described by him (W. Taylor 1925), built on the turret principle, has three lens-holding spindles, and two abrasive wheels operating simultaneously on two lenses at once, one roughing, the other trueing. With this machine, owing to the principle of grinding adopted, spherical surfaces may be ground indefinitely. Correct curvature is maintained by the grinding wheels being fed forward to compensate for their wear.

§68. In the following pages the reader will find described prism and lens making as carried out in the optical workshops of Adam Hilger, Limited.

The optical workshops of Adam Hilger do not, in normal times, carry out work on " production " lines ; the instruments in which they specialise are rarely put in hand in batches of more than three dozen. Yet, since more than once during my management of the firm we have been called upon to assist other firms by the supply of considerable quantities of high quality lenses and prisms, we have also studied appropriate methods of production. These methods were to a great extent worked out by ourselves and for that reason they were often different from anything in vogue elsewhere. Although doubtless other firms which had the problem of quantity production always before them must have developed methods ahead of us in many directions, there is plenty of evidence that in this country many processes developed at Hilger's in the last forty years have now become standard practice in the trade.

ROUGHING, TRUEING AND SMOOTHING

§69. Roughing. For roughing flat or curved work the simplest arrangement is to screw the roughing tool face upwards on a post around which the worker can gradually step sideways, thus changing the direction of his stroke relative to the tool. The lens is rubbed on the tool, with wet carborundum of 40 grain size, followed by 20, until the lens surfaces are uniformly greyed, and the lens is of the specified thickness. Such a simple device though in use in Hilger's within my memory, is now obsolete, but it is by no means to be scorned as a means of educating the beginner for a short time in the initial processes. It will avoid the

embarrassment and annoyance occasioned to his foreman by the work on which he is practising being rapidly ground too thin.

§70. Next in order of simplicity is the same arrangement but so made that the tool is supported on a vertically rotated spindle. The speed depends on the diameter of the tool—the quicker the better so long as

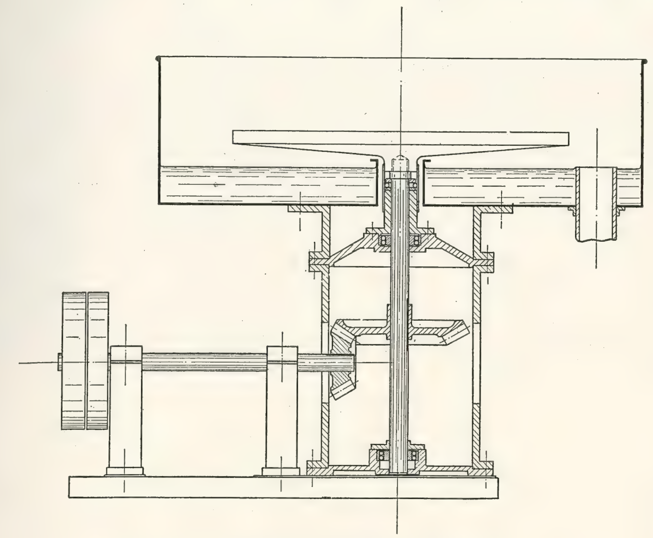


FIG. 9. Roughing Machine (Hilger).

the carborundum is not thrown off. A roughing machine of this type for flat work is shown in Fig. 9, designed by Mr. Dowell of the Hilger Company to my instructions in 1915. The flat tool needs re-turning every few months.

Fig. 10 shows a 4-spindle roughing and trueing machine which takes tools up to 12 in. diameter. Each spindle is independently driven by electric motor and each spindle is in a separate compartment to avoid the accidental mixing of abrasives. This machine is made by Messrs. Bryant Symons & Co., of Northumberland Park, Tottenham, London, N. 17, England.

§71. A new development in roughing technique was the use of machines with diamond charged copper (or soft iron) laps. Such laps were first described by Carl Zeiss, Jena (U.K. Patent 14126, 1907). When I was in U.S.A. in 1913 my friend Dr. C. E. K. Mees showed me an edging machine in use at the Kodak Works on which such laps were used and with his permission I had a machine on a similar principle made by Hilger's on my return to this country. We had several in use from early in 1914, two of which are still giving good service. This edging machine is described in §132.

Once the idea of the diamond lap had been adopted, the step to making other machines based on their use was an easy one, and a number of

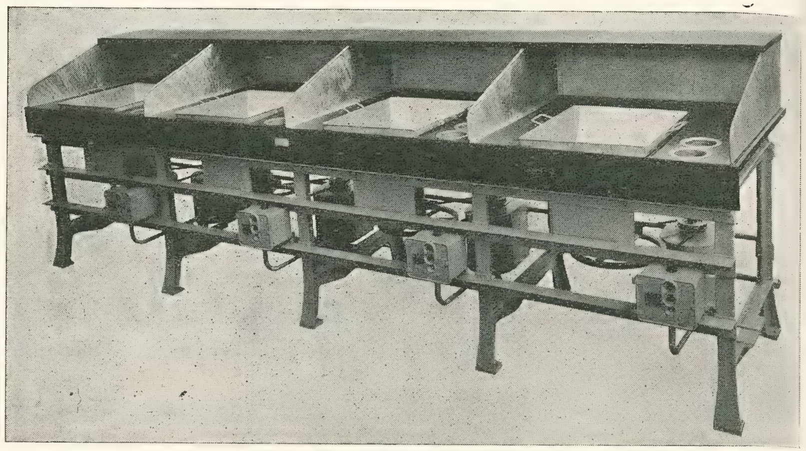


FIG. 10. Four-spindle Roughing and Trueing Machine.
(Bryant Symons & Co., London.)

machines were designed by Mr. Dowell (Chief Designer of Adam Hilger, Ltd.) and myself for slab milling glass blocks, for roughing lenses, and for other purposes. The slab milling of glass blocks merely required the use of an ordinary milling machine and a cylindrical diamond lap in place of the milling cutter, but the linear speed of the lap used by us is 1600 ft. per min. Ample lubricant of the soap emulsion type, like that

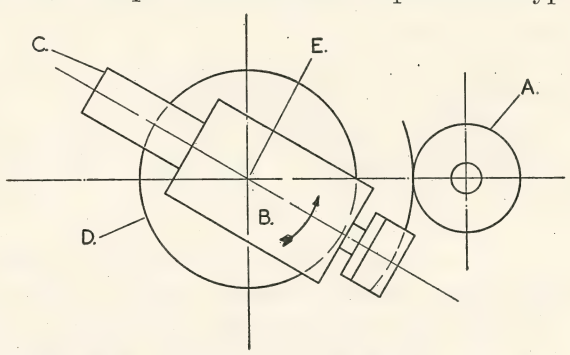


FIG. 11. Diagram of lens roughing machine with diamond lap.

used for turret lathes, must be used and the machine driven with sufficient power behind it, for if it slows down the lap is soon destroyed. For a cut of 4 inches wide removing $\frac{1}{4}$ inch of glass in one cut a motor of $1\frac{1}{2}$ horse-power is advisable.

The lens roughing machine made by us is shown in diagram in Fig. 11. A grinding tool A is mounted on a vertical spindle and the work to be ground is carried in a headstock B, with a horizontal spindle. The position of the headstock can be adjusted along a bar C mounted on a table D, which can be slowly rotated about a vertical axis E.

The grinding tool A is adjustably mounted so that the distance from its axis of rotation to the centre E of the rotating table D can be varied to suit the curvature it is desired to grind on the work, the position of the headstock B being adjusted along the bar C to give the desired thickness to the work.

When the headstock is set in this position the table D slowly rotates and feeds the work into the grinding tool A, the work also rotating on the horizontal axis of the headstock. A curve equal in radius to the distance from the centre E of the table D to the face of the grinding tool A is thus generated on the work as it is fed into the grinding tool. In 1917 we had ten of these machines in use.

§72. One may mention here the accurate machine grinding of prisms. The distinction implied by the phrases " milling " and " grinding " becomes perhaps a little obscure when the milling refers to a process employing such high speeds; but if the feed and cut are in the same direction the machined work has grooves due to inequalities in the tool. These grooves are very deep in terms of the unit of measurement of the optician, namely a wavelength of light.

Milling glass in this sense does not therefore give a grain sufficiently good to form the basis of accurate angling of prisms; for such work a cupped wheel used in such a way that the movement of the wheel on the work is across the direction of the feed and with a peripheral speed of, say, 3000 ft. per minute, is suitable. As far as I am aware, the first arrangement for the accurate angling of prisms by means of cupped laps was made at the Hilger works by the adaptation of a Brown & Sharp grinding machine. The prism was mounted on a turntable with an accurately divided circle and the faces were ground with the cupped diamond lap one after the other, each being brought into position by reference to the divided circle. I find from my notes that this machine was in regular use in November 1914 and was turning out prisms with an angle accuracy of about ± 3 minutes.

Diamond laps of the kind described above were used, but this is not essential. Very good results can be obtained with cupped wheels of corundum (sold under various trade names) although in our experience carborundum wheels are better. We have found the most useful types to be those described by the makers (the Carborundum Company) as Bond E.O., Grade S., Grit 90 and 220—the former for roughing operations, the latter for fine work. The linear cutting speed should be from 2000 to 4000 feet per minute, and the work should be amply

lubricated with the ordinary soap emulsion as used for turret lathes.

§73. Today we should prefer to use the Adcock & Shipley lens roughing machine (see below) (suitably modified) controlling the

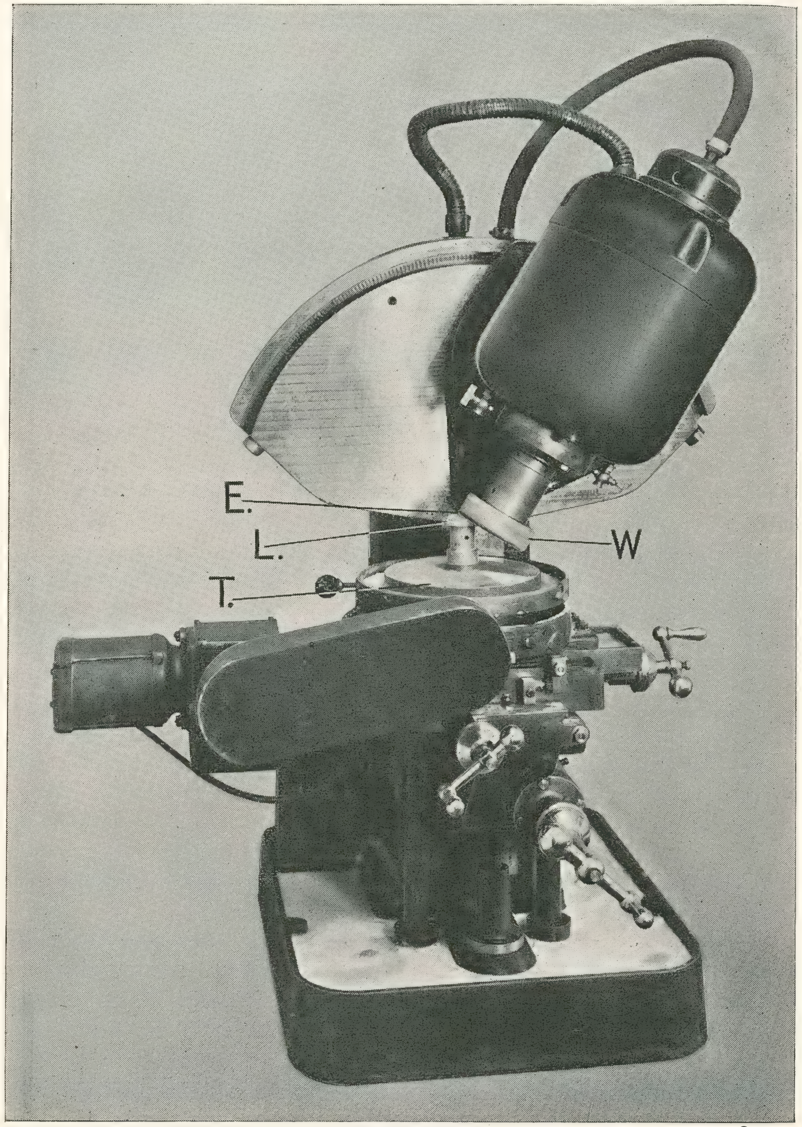


Fig. 12.

orientation of the prism by reflection from the surfaces of a standard prism by means of an Angle Dekkor (see §75).

§74. Sir James French tells me that during the last war Messrs. Barr & Stroud had a number of milling machines adapted for the milling of glass, using a special grinding wheel, but that they changed over, for most of their work, to automatic surface grinding machines which he designed, retaining however, two of the milling type for certain work.

§75. An Adcock & Shipley machine has been specially designed for roughing lenses. It is shown in Fig. 12. The diamond lap W is direct driven by a motor on the same shaft. Its cutting edge E must be exactly over the centre of the automatically rotating table T, and in these circumstances the lens L has a sphere generated upon it which depends on the diameter of the cutting edge of the lap and the inclination of the axis of rotation of the lap. The machine yields a very good surface and lenses roughed on it can be put straight into the block and immediately worked with trueing emery. [This machine can also be used with an emery or carborundum wheel for grinding lens tools to radius.]

Machines for trueing, smoothing and polishing are described in §93 *et seq.*

§76. Trueing and Smoothing

The words trueing and smoothing refer to grinding with successively finer grades of abrasive from the roughing up to the production of the final extremely finely ground surface which is ready for polishing. These processes require abrasives graded so as to be extremely uniform, and differing from each other in grain size in steps which experience has shown will produce most rapidly the finely ground surface which we may call finally smoothed, as described in §78.

§77. Let us suppose that we wish to prepare and polish a block 9 in. in diameter of lenses 2 in. in diameter. Unless considerable numbers are required of the same type of lens, we prefer to true the lenses separately by hand instead of in the Hilger or Adcock & Shipley machine, and we customarily use three grades of abrasives, trueing, fine trueing and smoothing. The trueing tool, when it has been made accurate by having the companion tool rubbed together with it with trueing emery, is screwed on to a vertical, rotating spindle; a small quantity of trueing emery is smeared on to the under tool and the lens (held with the fingers) is rubbed on it. Care should be taken to distribute the rubbing uniformly over the whole surface of the tool, which should rotate at about 120 revs. a minute. The work is continued until the surface is of a uniform grey all over, and the coarse grey due to the roughing process is entirely removed.

§78. This is of great importance. It is essential in passing from the use of one grade of abrasive to a finer grade, whether during the trueing or the smoothing process, that the holes or indentations left by the coarse grade should be completely removed by the finer grade of abrasive before proceeding to a still finer abrasive. In many cases, the surface of the glass may appear to the novice as being entirely smoothed to the necessary fineness, but experience has shown that there are still surface fractures and indentations left below and it is necessary to remove these before proceeding to a still finer abrasive. Again, before going over to a finer abrasive, the remnants of the previous one must be carefully cleaned away. This may be done by wiping with a soft sponge which is repeatedly squeezed into a bucket of water, but it is better to put the block under the tap.

If attention is paid to this portion of the processing the polishing time can be considerably reduced and the polished surface brought to a state of greater perfection.

For these reasons the lens must be very carefully examined with a magnifier to ensure that the coarse grain of previous emeries has been entirely removed, the examination being repeated at the application of each finer abrasive.

§79. On trueing the second surface of the lens the thickness should be measured and the trueing continued until the thickness is correct. The lens is then ready for blocking and polishing. One should avoid using more abrasive than necessary, particularly with the very fine grades, for if too much is used the work " rides " on the surface, the pressure on each grain being insufficient to crush the glass.

The Depth of Grey caused by Different Grades of Emery

§80. It is desirable to know the depth of grey caused by various grades of emery and we have ascertained this in the following way. A plate of glass was greyed on one side with emeries of grain size 10, 5, 2·5 and 1·25 (see para. 62), the degree of working down the emery being in each case that which is used in applying those particular grades of emery. That is, each of them except the last two were worked down until the emery had begun to lose its cut, while the last two (which are used as smoothing emeries) were worked down fully so as to produce the fine smooth type of surface which polishes readily. The plate was then polished with a one-sided pressure so that while about half of it was left with the original grey the other half was polished at a slight angle to the grey, giving Newton's fringes about 5 or 6 to the inch when a proof plane was firmly held in contact with the grey half. In this way it was possible to see what was the depth of the grain by counting the number of Newton's rings from the point of full greyness to the point where the greyness disappeared. The following were the results :

Grade of Emery.	Depth of Grey (Inch).
Fine trueing, 5·0. Worked till " cut " reduced.	0·00030 (a few deep pits were still left needing about 0·00020 to remove, making total depth of deepest pits 0·0005).
Smoothing, 2·5 worked right down	0·00011.
Smoothing, 1·25 ,, ,,	0·00008.

(*Note.*—The depth of grey does not include the under grey referred to in §29.)

Rayleigh (1901) found that a " very finely ground " surface was fully polished (except for very few small pits) by removing 0·00004 in. by polishing.

Coarseness of Grain

§81. A good idea of the coarseness of grain on a glass surface may be obtained from the limiting angle at which regular reflection is obtained of a bright object. This depends on the wavelength: for example, with a particular trueing emery it was found that an image of a light emitting the green line of mercury 5461 was detected at all angles of incidence greater than the angle whose cosine is 0·077. For light of wavelength 4358 regular reflection was seen at cosine 0·063.

§82. Occasionally in dry weather the rapid drying of the block during the smoothing process is annoying. In that case a modification of Plateau's solution may be used, made up as follows :

Fill a bottle $\frac{3}{4}$ full of distilled water, and add 1/40 by weight of sodium oleate. Shake well and allow to stand until dissolved. Then fill up with pure glycerine, again shaking thoroughly. Allow to stand until the solution is clear (usually a week or ten days), then syphon off, avoiding the scum which rises to the surface, and add 3 drops of ammonia to each pint of solution.

§83. Making a Polisher

We will suppose that a flat polisher, 9 in. in diameter, is to be made. The procedure is exactly the same for a spherical polisher with such modifications as are rendered necessary by the spherical shape and as naturally suggest themselves in carrying out the process.

Materials required

9 in. polisher with handle.

An optical tool amply bigger than the 9 in. polisher and accurately flat.

Bench with optical nose screwed thereto.

A pot of rouge (wet), and a water pot.

Brush for applying rouge.

§84. Pressing up

The polisher holder is stood face upwards in the middle of the larger tool and resting on its handle (see Fig. 13). On to it is poured from a

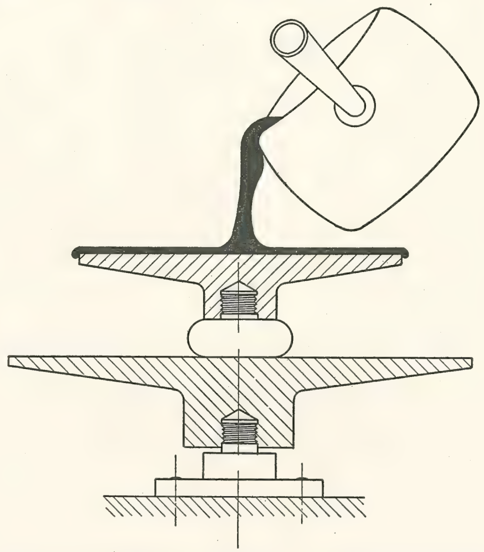
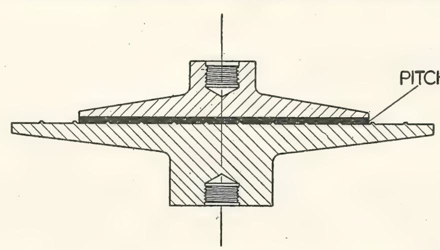


FIG. 13. Making a polisher. Pouring the pitch.

cooking pot about 6 in. diameter sufficient warm pitch, freshly ladled into the pot from the pitch cauldron, to form a layer $\frac{1}{4}$ in. to $\frac{3}{8}$ in. thick (see Fig. 13). The polisher holder should also be warmed, just so warm as to be not too hot to touch. If it is too warm the pitch will drop off, if too cold the pitch will not, as it should, flow right up to the edge. Trim the edge of the polisher with a knife until the pitch is flush with



TOOL FOR RETICULATING POLISHER.

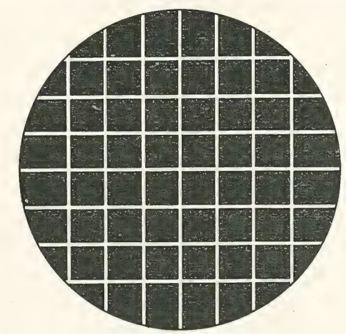
FIG. 14. Making a polisher. Grooving the surface.

the edge of the tool. Then lift the polisher by the handle, invert it and press it downward on a cold tool for a few seconds to flatten it approximately.

Take up the polisher by the handle again and warm the surface for a few seconds over a ring burner and press it down again once more on the cold tool. If the polisher is reluctant to separate from the cold tool, give its boss a sharp tap with a hammer. This process should be repeated until one sees that the surface of the pitch has touched the tool all over its surface, when it is ready for the next process.

§85. Grooving

A ridged tool called the Grooving Tool (see Fig. 14) is screwed to another nose or, if heavy enough, stands on the bench. This tool has a series of ridges about $\frac{3}{8}$ in. apart. Take the polisher, heat the pitch slightly on the surface and press it down on the grooved tool. Lift up, repeat the warming, and again press it down at right angles to the previous position, thus forming a reticulated surface (see Fig. 15). Gently



IG. 15. Pattern of grooves formed by two applications of the grooving tool in positions at right angles to one another.

press the polisher once more on the flat tool before cooling. Thoroughly cool the polisher by allowing cold water from a tap to flow all over it, front and back, until it is quite cold.

§86. Stamping

Now rouge should be painted on the polisher and a piece of wet gauze (about $\frac{1}{16}$ in. mesh) laid taut over the surface.

A flat 9 in. tool (and it must be thoroughly flat since we are now going to form the final polishing surface) is now warmed as hot as the hand can bear and rouge is painted on its surface. If the tool is too hot the rouge will dry off too rapidly. Press this down on the polisher. To hasten this process a 30 lb. weight can be put on top and left for about half a minute. The gauze is then peeled off, leaving the chequered polisher covered with fine reticulations, the purpose of which is to form a reservoir for the wet rouge which will be used in the polishing process.

Now rub on the polisher the flat tool, which will still be warm enough for this purpose. Remove the tool and allow the polisher to stand for about 5 minutes for the warm surface to cool, occasionally rubbing the surface for a few seconds with the flat tool.

§87. The polisher is then ready for use. If it is used for polishing small work by hand, it will require re-flattening with a slightly warm tool every few wets, a " wet " being the duration from applying fresh rouge to when it becomes too dry for polishing and begins to drag severely. In polishing, one should always carry on the wet until the drag is considerable, since it is in this part of the process that the polishing is most rapid and the conditions are best for producing a well-polished surface ; but when the rouge is drying, the polishing should not be too vigorous towards the end of the wet, or not only will the work become warm enough on the underside to distort the glass and prevent the formation of a true surface, but the polisher too may get warm and go out of shape.

If the polisher is used for block work the block helps to keep it flat and the polisher will keep true for four hours or more without re-flattening.

§88. In forming a polisher for lenses it is, of course, not possible to use a grooving former. The reticulations are then cut by hand in the following way. A file is sharpened to a sharp three-cornered point, and as a ruler a strip of brass about $\frac{1}{2}$ in. wide by $\frac{1}{32}$ in. thick, pressed firmly with the fingers of the left hand upon the surface of the polisher, is used. With this as a guide it will be found easy to cut the necessary grooves in the polisher with the point of the file.

§89. Making a Block of Lenses

The worker must be provided with

(1) A bench to which are screwed two iron nose pieces to which the tools can be screwed when occasion requires (see Fig. 16*b*).

(2) A block holder (see §90).

(3) A pair of optical tools of the required radius of curvature, accurately ground together and a wooden handle, Fig. 16*a*, to screw to either of them as required.

(4) A gas ring.

(5) A cauldron of mallet pitch.

The cauldron of hot mallet pitch (about 1 ft. in diameter) is placed on the bench, the hot mixture being a little stiffer than treacle. It is very important not to overheat the mixture, otherwise the pitch will harden. The mixture must be very well stirred immediately before use by means of a round stick 1 ft. long and 1 in. diameter

We will suppose that the lenses to be blocked are 2 in. in diameter. A sufficient number to form a block are placed on paper on a cold, flat, 1 in. thick iron plate, which is then gently heated with a Bunsen

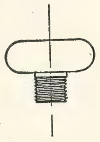


FIG. 16*a*.
Handle for optical tool or block holder.

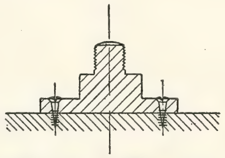


FIG. 16*b*.
Nose for holding tools on bench.

burner or gas ring to a temperature slightly hotter than can be comfortably borne by the hand. A blob of the melted mallet pitch is collected on the end of the stick, the stick being rotated so as to prevent the pitch dropping off ; the said blob is then laid on a cold tool where it is turned over and over to cool it. As it cools it is formed with the hand into a flexible, round-shaped piece about $1\frac{1}{4}$ in. diameter and of the consistency of putty. Still hanging on the stick, its lower end is allowed to rest on the back of one of the lenses and about $1\frac{1}{4}$ in. snipped off with scissors.

The process is repeated until there is a lump of mallet pitch on the back of each of the lenses, care being taken that the lumps are all of equal size. The lenses are then taken up in the hand one by one and the mallet at the back of each pressed on to the lens and worked up into a nearly hemispherical shape (see Fig. 17), placed in a wooden tray and

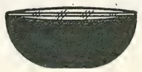


FIG. 17. Making a block of lenses. A typical pitch " mallet".

allowed to cool. It will usually be found that some of the mallets fall out of shape and one must go rapidly through them, re-shaping them with the hand until they are all cold enough to retain their shape approximately. They are then allowed to cool until all are of about the same temperature and cold enough not to go out of shape. Before allowing them to cool make sure that they are of equal thickness.

§90. The optical tool which is to be used for smoothing the lenses is now screwed to one of the noses and thoroughly cleaned. It is extremely important that every particle of dirt should be removed, both from this tool and from the surfaces of the lenses which are to be put in contact with it. There is always a possibility of a small spot of pitch finding its way to the surface of the lens or the tool; if this occurs it

can be cleaned off with a rag dipped in turpentine immediately before putting the lens on to the tool.

If the lens is placed on the tool while the turpentine is still wet on the surface, it will stay in position, or if no turpentine has been used, the tool should be slightly moistened. The lenses should be arranged not less than $\frac{1}{8}$ in. apart (though there is no harm in their being farther apart up to $\frac{1}{4}$ in. or more) and in sufficient number comfortably to fill the tool. The following numbers and arrangements make good workable blocks, but of course the more there are the better.

5 in a ring.		
6 round		1 = 7.
9	,,	3 = 12 (see Fig. 19).
10	,,	4 = 14.
12	,,	6 round 1 = 19.

The block holder is now heated on the ring burner until it is just so hot that one cannot touch it without discomfort for more than a fraction of a second. It must not be so hot that water sizzles on it. It is important that it should be heated uniformly, and for that reason the final heating should be carried out by holding it with the box-wood handle and waving it about in the flame to distribute the heat uniformly.

It is scarcely necessary to say here that under practical conditions of work it is not feasible to measure the temperature, nor is there any necessity for doing so.

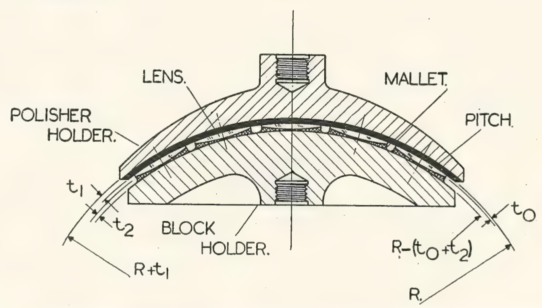


FIG. 18. Making a block of lenses. Sectional elevation of lens block and working tool.

§91. The block holder must now be gently placed centrally on the lenses which are arranged in the underneath tool and allowed to settle by its own weight. It will gradually soften the mallets and it should be allowed to do so until their thickness is between $\frac{1}{4}$ in. and $\frac{1}{2}$ in., say about $\frac{3}{8}$ in. Keep a watch all round to see that the mallets are settling down equally all round the block and when they have settled down to the thickness stated above, cool off the block holder by sponging with cold water. Leave the block till cold, when it is ready for work to be started.

The block of lenses is shown in section in Fig. 18, lenses uppermost, with a polisher in position. Fig. 19 is a view of the block from above. The block should not be removed from the forming tool until one is ready to smooth it, as otherwise, even if it is cold, the lenses will shift

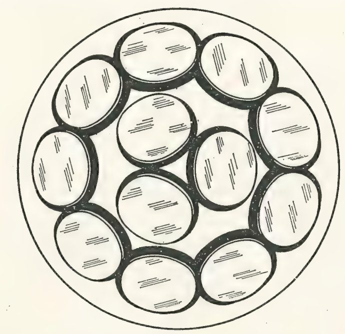


FIG. 19. Making a block of lenses. Plan of completed block.

and the smoothing will take longer. Supposing the smoothing tool is ready, the block is pulled off and smoothing can at once commence. If the work has been carefully done it will be found that the whole surface becomes uniformly ground by the smoothing emery within a minute's rubbing.

§92. The above description applies to the case where convex surfaces are to be polished, so that the lenses with their mallets are arranged face downwards on a concave tool. If a concave surface is to be worked they are, of course, arranged on a convex tool, the concave blockholder being lowered on the mallets. The subsequent procedure is exactly the same, except that as soon as the tool begins to settle down on the mallets, the pair of tools with the lenses between them may be turned upside-down, since it is more easily seen whether the operation is being performed satisfactorily—it is important that the block should be central and the mallets of nearly equal thickness all round the outside of the block.

§93. Polishing Machines

Fig. 20 shows a 4-spindle grinding and polishing machine of a type which has been in use for very many years, but is of recent construction. The tool screws into position at the top of the spindle which lies within the dishes A. When the top tool or polisher is in position the arm B is raised and the ball at the end of the pin P (see Fig. 20) lowered into the socket which is screwed into the boss of the upper tool. The spindle in question is then started by the lever L (the four sections of the machine run independently of each other) and the arm reciprocates with a stroke which can be varied by the adjustment provided at the

crank disc C. The machine is independently driven by the motor M.

The makers are Messrs. Bryant Symons, Ltd., Northumberland Park, Tottenham, London, N. 17.

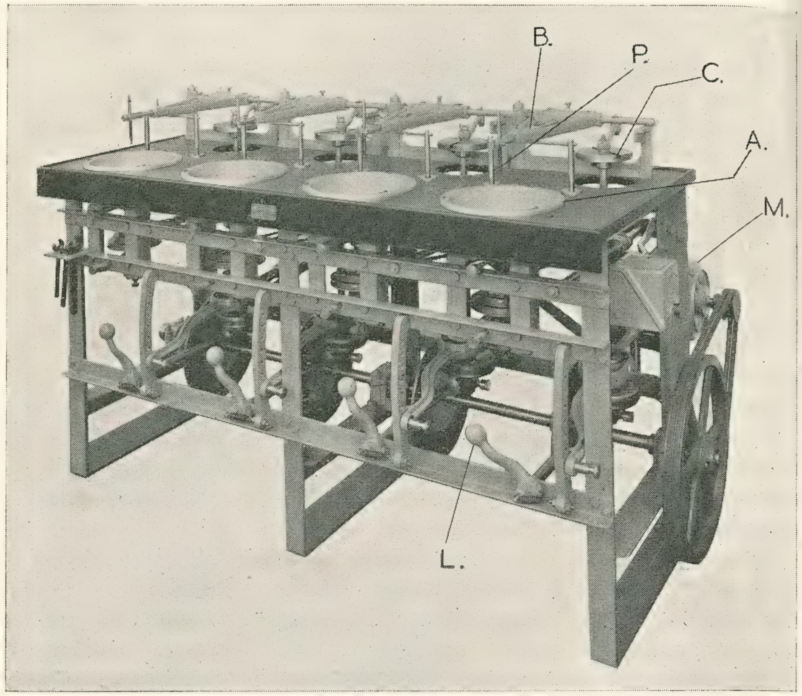


Fig. 20. 4-Spindle Polishing Machine. (Bryant Symons, London.)

We find that with polishing machines of this type the following relations between rate of cross stroke to that of rotation of the spindle give good results—

Diameter of Block.	Spindle Rotation revs. per minute.	Cross Stroke (forth and back) number per minute.
13″	24	48
9″	30	60
$6\frac{1}{2}''$	40–50	80–100
$3\frac{1}{2}''$	60–70	80–100
Single lenses, 1–$1\frac{1}{2}$ in. diameter.	120	90–120

§94. Figs. 21 and 22 show parts of a 24-spindle machine for lenses up to $1\frac{1}{2}$ in. diameter and a 6-spindle machine for blocks up to 6 in. diameter, both designed and made by Adam Hilger, Ltd. The design of

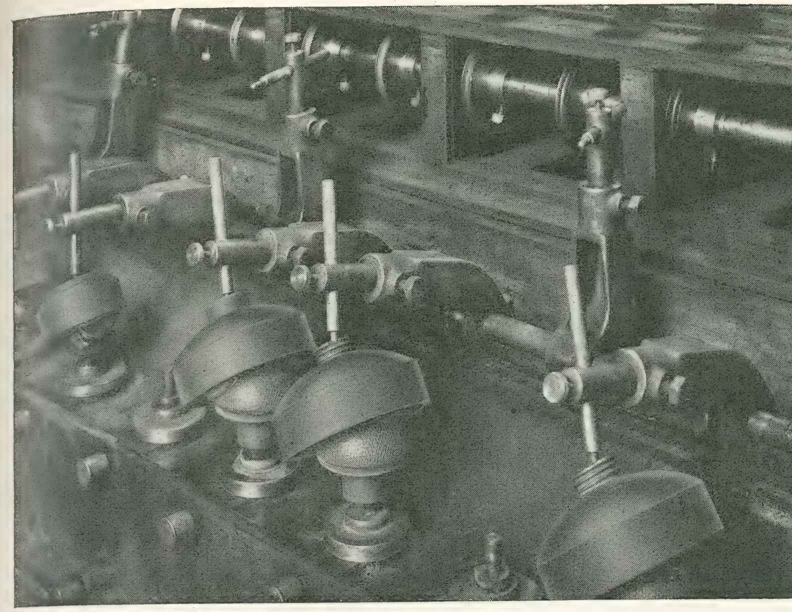


Fig. 21. 24-Spindle Polishing Machine. (Hilger.)

Fig. 22. One spindle of Hilger 6-Spindle Polishing Machine.

these machines aimed at combining all the essential movements with the greatest simplicity of construction, owing to the urgency of installing them. For this reason the frames were made of wood. The

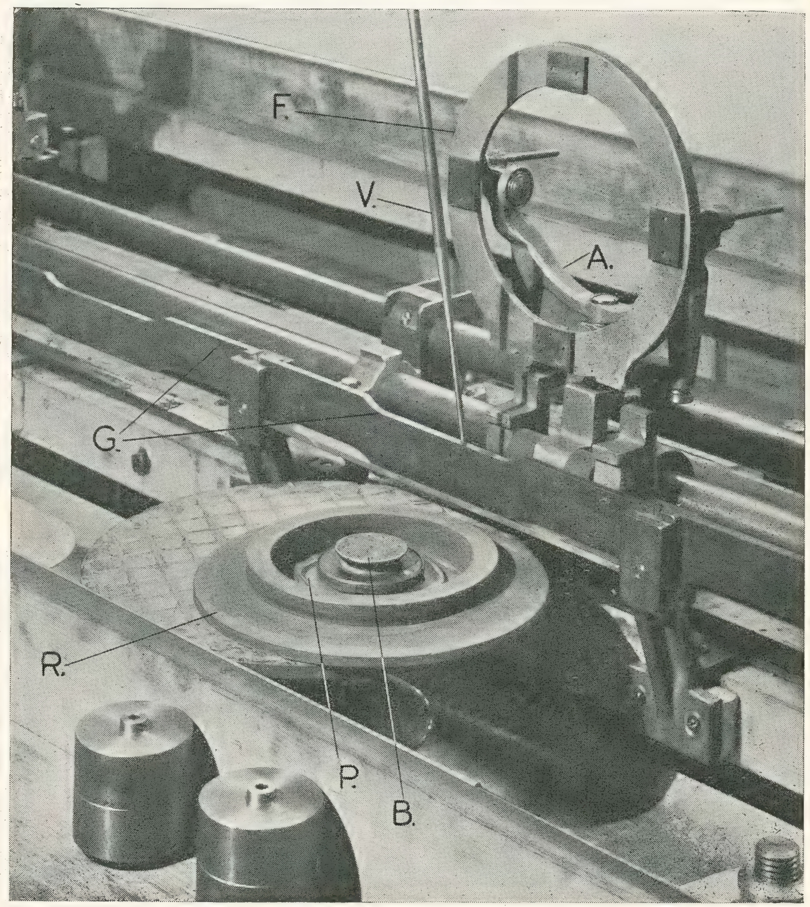


FIG. 23. Detail of Single Surface Machine for high accuracy. (Hilger.)

machines differ from the traditional type in which there is a separate reciprocating arm for each spindle, for all the driving pins in each row are driven from one shaft.

Single Surface Machines for High Accuracy

§95. It will be seen later (§155) that in working blocks of prisms one cannot usually expect a greater accuracy than from 2 to 5 minutes in the angle. Further, in working singly any type of flat work, including

plane parallel windows, and plane mirrors, very high accuracy of surface cannot be attained with ease and certainty by handwork since holding the work entails a certain amount of distortion due to temperature differences. Single working therefore, although sometimes unavoidable, demands great skill and patience if it is done by hand.

In such hand working there are two opposing actions with which the optician has to contend. Since he holds the work with his hands or fingers he makes it warm, so that in the early stages of a wet the bottom surface of the work is relatively cold and therefore when it is removed from the polisher and the temperature is allowed to become uniform the polished surface becomes convex. Towards the end of a wet the side which is being polished becomes relatively warm and the opposite action takes place. Thus the hand-polished surface of, for example, a window, usually has the characteristic shape of a surface slightly concave in the middle with the edges " off ".

There is a further difficulty. In the case of a prism held in the fingers there is a tendency to tilt it when polishing and thus produce a surface with the edges rounded off.

The effect of difference of temperature can be annulled to a great extent as a result of experience, the rate of polishing being adapted to the warmth of the fingers. The skilled optician is assisted in obtaining this balance by the feel of the work. If polishing is taking place on the outside, the work is felt to grip the polisher on the outside, whereas if polishing is taking place in the middle the work easily swings. Thus, uniform polishing of the whole surface has a characteristic feel which the experienced man learns to recognise.

The tendency to tilt can also be avoided by experience, the pressure of the fingers being suitably adjusted, but long practice is required to obtain good results with hand polishing and even the most skilled optician sometimes has to try repeatedly to reach the desired goal.

§96. Numerous devices have therefore been adopted by us at different times to obviate the necessity of hand polishing when repetition work is being done. Nearly thirty years ago I decided to adopt a method of mechanically holding the work in machine polishing which applied the force which pushes the work about on the polisher in a plane as near the polisher as possible and applying downward pressure by means of a loose toggle joint.

§97. Very good work was done by adopting this principle in various ways, but in the ordinary type of machine, described above, since the work traverses the same zones of the polisher repeatedly, it rapidly makes the latter go out of shape and the constant reflattening of the polisher causes considerable loss of time. Mr. Underhill, Head of the Optical Department of Hilger's, a few years ago introduced a device to retard this local deformation of the polisher, in the shape of a heavy

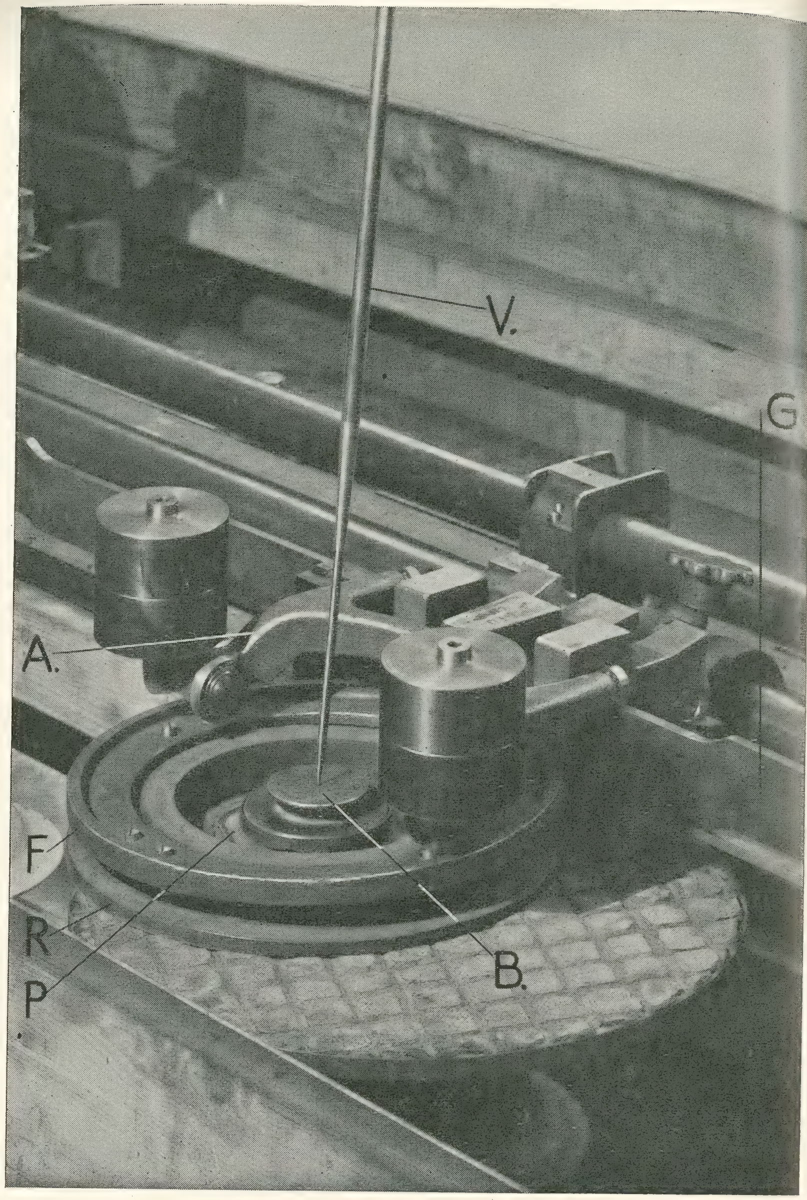


FIG. 24. Detail of Single Surface Machine for high accuracy. (Hilger.)

ring surrounding the work and moving with it. Improvements were added from time to time by us, until the final form of machine shown in Fig. 23 was arrived at, which has been found to produce single surfaces of remarkable accuracy.

The wooden frame, although not elegant, is braced by struts and ties and is satisfactorily rigid.

§98. The machine includes several devices not present in the earlier ones. One of these enables the operative to control the parallelism of a plate, or the angle of a prism. The top of the pressure block has a number of small recesses into any one of which the pointed end of the vertical rod can be placed thus applying the pressure towards that part of the work which requires reducing in thickness.

The constancy of the applied pressure and of the other conditions makes it very easy for the worker (who has an interferoscope conveniently near) to alter the angle in accordance with what is shown by test to be necessary.

§99. Secondly, there is a device to correct the tendency of the polisher to become concave or convex. This consists of a rocking arm *A*, bearing two weights *W*.

The stroke of the machine is set so that the centre of the ring oscillates symmetrically on each side of the spindle. The length of stroke is such that the ring projects over the edge of the polisher at each extremity of the stroke. It is found that even with the most careful adjustment of stroke the polisher gradually becomes either concave or convex, and it is the purpose of the rocking arm to control this.

The rocking arm engages through ball bearing runners with a guide *G*. When the guide strip is in the position shown in the figure then as the ring passes over the central position the right-hand side of the rocker is lifted so that only the left-hand weight bears on the ring. The left-hand side of the ring travels approximately as far as the centre of the polisher, and during this movement and on its return to the same place again the effect of the weight is, therefore, to make the polisher concave. When on the return stroke the ring is in the central position again, the left side of the rocker is lifted and the right allowed to sink so that the right-hand side of the ring is weighted. Thus throughout both the forward and return parts of the stroke the tendency is the same, namely to make the polisher concave.

If the polisher is already concave the reverse effect can be produced by turning the guide strip upside down, when the action of the rocker will be to apply pressure always towards the outer portion of the polisher, thus tending to make it convex.

§100. Finally one may mention that the driving shaft is operated by a double crank so that two sine motions are superimposed on it; the one carrying the stroke right across, the other a small and much more

rapid reciprocating stroke. The effect is to simulate the customary action of the skilled worker who is touching up work individually in the attempt to produce an accurately flat surface without spoiling the flatness of the polisher.

§101. Polishing Blocks of Lenses

In polishing blocks of lenses, whether by hand or by machine, it is usual for the convex surface to be underneath. For simplicity of description we will suppose that we are polishing a block of convex lenses. It is assumed that the following preparations have been made :

(*a*) The tools have been ground to a good fit and of the correct curvature so that the tool on which the polisher is to be formed exactly fits the proof plate (§112).

(*b*) The polisher has been made and formed.

(*c*) The block of lenses has been trued and smoothed.

Wet rouge is painted on the polisher with a soft bristle brush and the polisher is then rubbed on the forming tool. The polisher is then placed gently on the block of lenses and polishing is begun. The process of polishing by hand consists of pushing the polisher to and fro over the block of lenses, the stroke being a long ellipse, a slight rotation being given to the polisher at the end of each stroke. In machine working the upper tool naturally rotates since it is carried round by the rotation of the block when the polisher is nearly central with the latter.

In machine polishing, the block of lenses having been screwed to the work spindle, the polisher, charged with rouge and freshly rubbed on the former as above, is placed gently on the block, the reciprocating arm of the machine brought over and its driving pin placed in the socket which is screwed to the polisher (see §93). The work spindle and reciprocating arm are then started.

§102. The quickest rate of polishing will be achieved when the polisher makes contact with every lens all over its surface (but see §108) and it is usually unnecessary to apply any weight beyond that of the polisher holder and the arm of the polishing machine.

§103. Three conditions are essential in order to achieve this degree of contact, namely that the final smoothing emery should be worked down as fine as may be possible without scratching the work, that the true tools should be well ground together with as fine emery as feasible (2·5 grain), and that the polisher should be an accurate fit on the forming tool.

The first condition demands some degree of skill and experience. It is important to maintain the abrasive in the correct condition of wetness ; if too wet it will scratch and if too dry it will not produce the finest grey.

The second condition is a matter of patience, frequent checking and scrupulous avoidance of letting the tools get far out of truth.

The third condition is best achieved by rubbing the polisher on the cold forming tool on the machine for five or ten minutes, using a weight of about $\frac{1}{2}$ lb. per square inch of polished surface. A sign that the polisher fits the forming tool on which it is formed is that when working of the polisher on the tool begins the rouge quickly changes colour to a light yellow over that portion of its surface which fits the tool—that is when using cast-iron tools. When this effect extends over the whole area of the polisher some more rouge should be added from the brush and the polisher run on the tool for one or two minutes longer.

§104. The polisher is kept wet by spraying the forming tool with clean water from a scent spray or from a brush while the polishing is proceeding ; the working period from the moment of applying fresh moisture to when the work is dry enough to need more moisture is called a " wet ".

On repetition work which is not of the highest quality it is permissible to add water to the polisher from the brush while polishing is proceeding, but when the polisher requires new rouge it should always be removed from the block, rouge applied to the polisher, and the latter then rubbed on the forming tool before replacing it on the block of lenses.

On a convex block the polisher will naturally be removed, wetted and replaced ; if a concave block is being worked with a normally offset stroke it is permissible to add clean water to the polisher when this is uncovered by the block. With care the polisher can be maintained in that condition of moisture which gives rapid polishing without undue heating effects.

The polisher should not be kept so wet as to prevent it eventually almost drying up so that the polisher drags distinctly on the work. It is during this part of the process that the polishing is most rapid but it is at this stage also that the most heat is generated. In polishing by hand it is not likely that much harm will result from this because the work then becomes so strenuous that it is not likely to be carried on at a rate which will cause much heating. In machine work, however, this stage must be carefully watched and not allowed to proceed too far ; otherwise the polisher will be deformed and as a consequence the lenses on the block will become a bad shape.

Polishing deep curves

§105. At this stage it is necessary to recognise that in polishing deep surfaces certain phenomena become obvious that are not appreciable with shallow ones. If tools *A* and *B* (Fig. 25*a*) are ground together with an appreciable thickness of abrasive, their surfaces may both be spherical but the radii of curvature will differ by the thickness *T* of the

abrasive, and if they are cleaned and put into contact they will bear in the middle (Fig. 25*b*). The thickness of a well-rubbed-down smoothing emery is about 0·0002 in. and this is quite sufficient to produce a very

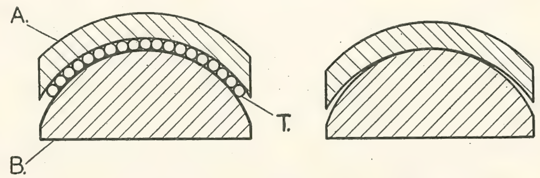


Fig. 25*a*. Fig. 25*b*.

Effect of thickness of abrasive when grinding deep curves.

noticeable effect in a pair of tools subtending an angle of 120° and with a radius of curvature of less than, say, 4 in.

§106. If two such tools are put together, they will be found to swing around the middle. If, however, the convex tool is now used to form a polisher, the said polisher will be of the same radius of curvature as the smoothed block of lenses; or rather, very slightly less, since in forming the polisher the forming tool is itself polished to a slight extent and thus slightly reduced in radius.

It should be found, therefore, that the polisher thus formed fits the surface of the smoothed lenses almost exactly, and that polishing should commence uniformly over the whole surface.

§107. The novice, then, should not suppose that it is necessary or desirable that when he has trued his tools they should fit over the whole surface. It is normal and correct—if they are deep and of short radius—that they should swing about the middle.

§108. There is, however, another point to consider; the tools after smoothing have a grain which has a not entirely negligible depth (see Fig. 26). As pointed out above, in forming the polisher this grain is

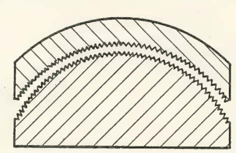


Fig. 26. Grain of surface of tools.

partially polished away and the radius of curvature somewhat reduced. The polisher, therefore, may be expected to commence polishing the outside of the block of lenses first. In so doing it soon begins to accommodate itself to the shape of the block, becoming slightly less deep; simultaneously with this, however, the outer portion of the lens block polishes before the middle and thus the lens block gets a little

deeper. Thus polisher and block rapidly come into good contact and the polishing takes place uniformly.

§109. Thus the worker must regard it as perfectly normal for there to be a slight tendency in deep blocks of lenses or in deep single lenses for polishing to commence on the outside. Since the effect depends very much indeed on the depth of the surface, it requires a good deal of experience to recognise when one is dealing with the normal and indeed desirable condition, or when on the other hand one is in the presence of defective processes such as those mentioned below.

The above illustrations show the surfaces central with each other. Actually in polishing deep surfaces the polisher is always off-set and the effects just mentioned are less obtrusive.

§110. It is essential to keep the block under the closest surveillance during the first half-hour of polishing. Certain appearances may be observed which, though usually indicating that the conditions referred to above have not been strictly complied with, may not justify repeating the processes concerned.

§111. Again assuming that it is a block of convex surfaces which is being polished and dealing first of all with deep surfaces such as those which we have just been considering, the following appearances may be encountered when the first or second wet is completed.

(*a*) The centre lens is slightly polished while the lenses of the outside of the block are quite grey. To correct this the polisher may be rubbed again on the forming tool, the latter being warm. On recommencing to work the block the block holder should be very slightly warmed. Polishing should be carried out on the machine for two wets with a weight of 5 lb. on the pin of the machine for a block 4 to 6 inches in diameter. If the polisher takes very strongly in the middle the effect may be remedied by relieving the middle of the polisher by widening the grooves with a sharp knife.

(*b*) The centre lens is almost entirely grey, the edge of the block being partly polished (*i.e.* the reverse of the condition described under (*a*)). This indicates that the forming of the polisher (see §86) has not been completely performed. The treatment for this is the same as for (*a*) except that the block holder should not be warmed at all.

If this does not suffice, the polisher should be relieved, this time on the outside.

(*c*) Each lens in the block is polished round its edge, but all are grey in the centre. This is the worst case of all to put right and is due to the mallet pitch being much too soft and the tools not a good fit. The only cure for this condition, short of reblocking with good mallet pitch, is to remove the stroke off-centre as far as possible and to avoid rubbing up the polisher at all. The polisher will then gradually deform to the deeper curve possessed by the block, and the lenses will gradually move

so that each lens in the block will polish all over ; polisher and block accommodating their shapes to suit each other ; but this is a poor remedy and cannot be expected to produce first-class work.

No attempt should be made to use the test plate until the polishing process is satisfactorily mastered.

§112. The Use of the Test Plate in Polishing Blocks of Lenses

As soon as the polishing process has been mastered and the use of the test plate learned (see §176) the latter should be used during the early stages of polishing, when the following appearances may be encountered :

(*A*) The block polishes evenly, the shape of the lenses being, however, more concave or convex to the test plate than will be permissible in the finished lens. This is due to the forming tool not having been quite true to the test plate. This can be corrected by removing the stroke more off centre (convex block) or nearer the centre (concave block) and it will be found that, if the polisher is the same size as the block, the test plate shape will slowly alter to perfection, remaining spherical meanwhile. If astigmatism develops during this correction process it may be due to (*a*) the polisher being too large or too small, (*b*) the mallet pitch being too hard. A quicker method of correcting this fault, but one requiring careful observation, is to continue the polishing with the stroke as it was at first until the lenses are polished, and only then to set the stroke off centre (as recommended above). If now the block holder is gently warmed with a Bunsen burner—very gently, indeed, the temperature should not be raised more than about 5° to 7° C.—it will be found that the lenses quickly alter until they fit the test plate. What happens in this case is that the mallet pitch, being softened, permits the lenses to set themselves in contact with the polisher, which is itself deformed by the increased offsetting of the stroke.

(*B*) A block may start polishing well but develop " edge off " in the latter stages. This form of astigmatism is usually due to the polisher not being well covered by the block, for instance a concave block may travel to within $\frac{1}{4}$ in. of the edge of its polisher and no further. The rim will in the course of time become higher than the rest of the polisher, turning off the edge of the block more and more. It may be noted that the middle of a block never appears turned down under ordinary conditions. One important condition for avoiding astigmatism is that any given zone of the polisher should sweep as much of the block as is consistent with the maintenance of the required general shape.

§113. Detaching the Lenses from the Block

The mallets can easily be detached from the block with the lenses adhering to them by giving the former a sharp blow with a hammer

through the intermediary of a pointed rod of steel ; the rod and lens can be held in the left hand to prevent the lens falling. The lenses are then easily separated from the mallets by putting them, mallet side down, in an ice box containing "Drikold" (solid CO_2).

Single Surfaces, Machine Polishing

§114. When polishing deep single surfaces by machine no trouble will be experienced if the tools are in good condition and correct to the test plate.

In smoothing these surfaces it is a good general rule that the smoothing tool should be on the rotating spindle, whether the surface to be smoothed is a concave or a convex one. The lens will then be moved with an off-centre motion which will have the effect of keeping the tool a good shape. The polisher should be the same size as the lens and well stamped. Little or no grooving is necessary to alter the figure of the lens if this is already good.

§115. The most satisfactory machine polishing stroke is symmetrical, and of such a length that the centre of the polisher travels one-third of the way towards each edge in turn.

Barring the occurrence of scratches, a dozen or more lenses may be left on the machine spindles until polished and will need very little individual attention.

§116. Should the tools be in such a condition that the lenses, while polishing evenly, are not sufficiently close to the test plate, they should be left until nearly polished. The polisher should then be drastically relieved in such a way that it only touches where material must be removed to bring the shape right. For example, a convex surface showing concave to test plate (*i.e.* the edge must be polished more than the middle) would be treated by removing the centre of the polisher to the extent of one-third diameter, retaining the symmetrical stroke.

Note on Optical Tools

§117. When working with deep lenses of any radius, it must be recognised that on account of the presence of the layer of emery grains the radius of the smoothing tool is not the radius produced by the grinding.

If, however, the tools are ground together with a medium emery, *i.e.* neither the very finest nor yet a very coarse grade, and the polisher forming tool when polished fits the test plate, the presence of emery when the lens or block is smoothed will ensure that a curve of that radius is generated.

§118. Note that these tools when rubbed together dry will not shine all over and no attempt should be made to make them do so. It is sufficient to clean the emery off and dry them after they have been

ground together and examine them by eye. Any departure from sphericity or fit will show up as an unequal blackening of the surface.

Further Remarks on Machine Polishing

§119. In polishing flat work which is rigidly blocked (for example, in plaster or direct on the tool with wax, see §151 and §155) the ideal arrangement is for the polisher to be a little smaller than the block and for the block to be underneath. If the diameter of the work in the block is 13 in. the polisher may conveniently be 11 in. and the stroke such that the centre of the polisher moves from 1 in. on the left to 3 in. on the right. At the extremity of its motion, therefore, the polisher will overhang the block by 2 in.

To put this in a more general form, applicable when the polisher and block are of other dimensions (but the polisher smaller than the block), we may say that the polisher should move to one side so that its edge coincides with that of the block and in the other direction until it overlaps the block by from one-fifth to one-quarter of its own diameter.

§120. In polishing lenses which are mounted on mallets, one must take into consideration the fact that the mallets are, like the pitch polisher (though to a less degree), subject to flow and if the lenses are not held in position by the polisher during the action of polishing, the mallets will sink by different amounts and the figure of the lenses will suffer.

Large Blocks of Lenses either very shallow or flat

§121. The following remarks apply only to comparatively shallow blocks of lenses on mallet pitch, and in particular to blocks consisting of a large number (25 to 40 per block).

The polisher should be the same diameter as the block. It should be well stamped with clearly defined grooves. In polishing the flat sides of plane lenses the tool used for smoothing should be as flat as possible, the error should certainly not amount to more than three or four Newton's fringes over the whole area, and should be slightly convex for preference. A tool exactly fitting the smoothing tool should be available for forming the polisher. This will ensure that the grey is evenly removed. The stroke on the machine should be such that the centre of the upper member (block or polisher—see §101) moves between the limits $\frac{1}{4}$ in. to $4\frac{1}{2}$ in. off centre. The upper element, whether block or polisher, gradually becomes more concave (or less convex). Flatness is achieved, therefore, by discriminating reversal of block and polisher.

Deep Blocks of Lenses

§122. In polishing deep blocks of lenses (say comprising an angle of 120°), the convex surface should be underneath (whether it be block or polisher), the polisher and block should be of equal size, if for no other reason than to keep the mallets in shape, the stroke such that the concave surface at its extreme movement in one direction projects over the convex one by about three-fifths of its diameter and at the other extreme projects by about one-fifth of its diameter.

For blocks of lenses of intermediate depth the procedure should also be intermediate to the above extremes.

§123. The total pressure of the polisher on the work (including that due to the weight of the arm of the polishing machine) should be $\frac{1}{2}$ lb. per square inch of the total surface to be polished.

§124. If a convex lens or block of lenses is found to be polishing in the middle, leaving the edges grey, it is evident that more glass should be polished from the area near the outside or periphery of the block. This may be done by :

(*a*) Relieving the centre of the polisher by scraping the pitch surface, or, better still, by opening the grooves of the reticulations ; or

(*b*) By adjusting the driving arm of the polishing machine so that the polishing tool is working more on the outside of the block of lenses.

§125. The method of correcting the opposite fault—namely the block or lens polishing on the outside, if it occurs beyond the degree explicable by §109—is effected by reversing the process mentioned above.

These last-named methods of correction, however, should not be needed if the tools have been well trued with fine emery, and the polisher has been formed to fit truly on the appropriate tool.

Precautions to avoid scratches, " digs " and " sleeks "

§126. I cannot do better than insert here a translation of a passage from Dévé's book on this subject, which can be heartily endorsed as a statement of an ideal to be aimed at :

" The risk of scratching glasses in the course of surfacing requires exemplary cleanliness and care to avoid the accidental mixture of abrasives of different grain size, or grains of dust falling on the tools or polishers. The ground, the walls and the ceiling of the workshop ought to be sound, easily washable, and covered with varnish paint. The colour of the paint should preferably be an imitation of red marble up to a height of 2 metres, because this renders soiling by the polishing materials less unsightly. Framed windows in the ceilings are absolutely to be forbidden, for the dust accumulates in the angles and the least breath of wind blows it into the workshop. One can cite as a model installation that of the polishing rooms of the ' Atelier de Construction de l'Artillerie ' at Puteaux. There are no windows, properly so-called, but a fixed waterproof glazing. No air is admitted to the rooms except

what is filtered through a special ventilator. Large channels in the angles of the rooms bring in the air and evacuate the used air. In this way smoke and dirt have no access to the optical shop. The floor is covered with thick linoleum on which the glasses can fall without too much risk of breaking or scratching. These precautions would be illusory if the workmen introduced with them the mud or dust of the street. Access to the workshops can only be obtained by passing through a vestibule, where the outdoor shoes are changed for those of the workshop and the overalls put on, as is customary in bakeries. A boiler suit is superior to the white blouse which is still in use in old-fashioned optical shops. The wearing of flowing vestments in the neighbourhood of gears and belting is imprudent. Along the workshop walls and away from the daylight are little recesses in which the workmen can go to examine by artificial light the glasses which they are polishing. These recesses should be illuminated by approximately monochromatic light, preferably a mercury lamp. Finally, it is necessary to maintain a constant temperature in the workshops which use pitch polishers. If, for example, in winter one neglects one day to heat the workshops, pitch prepared to have a suitable viscosity at 18° C. would be too hard at a temperature of 10° C. and one would risk having numerous surface scratches. The good optician should, as befits a very delicate operation, be careful, attentive, methodical and clean. The good optician habituates himself never to soil his left hand, using only his right hand for handling the lenses, abrasives, greasy bodies, etc. He keeps his left hand always clean in order to handle a caliper or other instrument, some delicate piece or the handle of the optical tool." (Free translation.)

One may add that the hands and benches should frequently be washed, especially after the use of carborundum or emery, while cleaning rag and camel hair dusting brush should be kept in a covered enamelled jar like those used in the domestic larders for keeping sugar, rice, etc. For my own use I always keep an old linen handkerchief which has been boiled in distilled water, and a camel hair brush which has been cleaned in absolute alcohol, and use them for the final cleaning. If kept in a covered jar they will remain grease-free and very effective in cleaning optical work for some weeks, even when in daily use.

CHAPTER VI

FINISHING THE LENS: CENTRING, EDGING AND BALSAMING

§127. Centring and Edging Lenses

The centring and edging may be considered as one process. The lens is stuck on to a chuck as shown in Fig. 28 in the following way. *C* is a tubular chuck about 0·05 in. smaller in diameter than the lens, with a rim bevelled inside and outside to a profile angle not greater than 60°. The optimum angle depends on the depth of the surface, but 60° will be found to accommodate all but the very deepest of lenses. A small flat (about ·002 in.) is ground on the point of intersection of the bevels with very fine emery (on a flat piece of glass). For accurate centring it is important that the two bevels and the flat should all run true. The truth of the flat may best be tested by holding against it a piece of flat glass and observing the reflections in the surface of the latter while the chuck is running.

§128. The chuck is gently heated with a Bunsen burner to such a temperature that if a piece of pitch of suitable softness (about 3 mm. hardness at shop temperature, see §48) is applied to the end of the chuck rim, it melts and adheres to the chuck in a viscous condition. It will be found that after a little practice a rim of softened pitch can be formed. If a convex surface is to face the chuck, this rim of softened pitch should lie on the inside bevel, and conversely for a concave surface. If then the warmed lens is applied to this it will adhere but can be moved about so as to centre it.

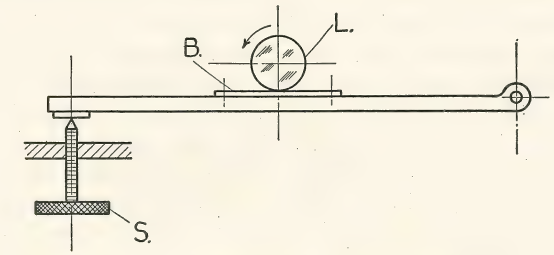


FIG. 27. Lens Edging and Centring.

§129. The lenses are kept warm on a three-legged hot plate heated by a ring burner, and covered with soft paper on which not more than twelve lenses are put at one time. When three lenses are left on the hot plate, a further nine are put on to warm, the remainder being kept in a covered tray.

§130. Two methods of observing centring can be employed. In the first the reflections of a distant light source at the front and back surfaces of the lens are observed and the lens is pushed about with the fingers of the right hand while the chuck is kept of a suitable warmth by careful use of a Bunsen burner, the rotation of the chuck being arrested by the left hand while the lens is pushed central. When both the reflected images remain stationary the lens is central with its axis of rotation and perpendicular to the optical axis.

This method, however, imposes a high degree of accuracy in a respect which is not essential. It is very important that the centre of the lens (*i.e.* the thinnest or the thickest place) should be on the axis of rotation, but it is not essential, or not essential to the same degree of accuracy, that the centres of the curved surfaces should both lie on the axis of rotation. Now it may very well happen that a small piece of dirt may lie between lens and chuck and prevent both conditions being simultaneously arrived at. The operator is then tempted to force the lens into position, often with the result of causing a scratch.

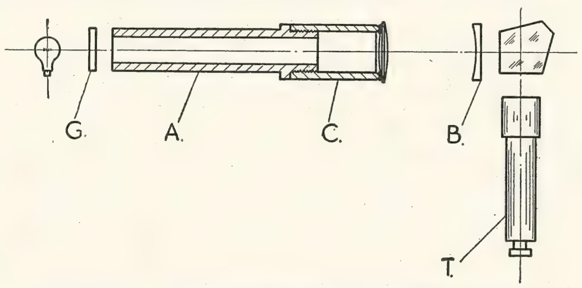


FIG. 28. Centring a lens by transmitted light.

It is therefore often preferred to observe not the reflected images but the transmitted images by observation through the hollow mandrel *A* of the edging lathe (see Fig. 28). The worker sees through the telescope T an image of the graticule *G*. An auxiliary lens (*B*), of appropriate focal length, must be employed as shown in the figure. The observer's only concern then is to shift sideways the lens which is being edged until the image seen in the observing telescope *T* is motionless.

Whichever means of observation he adopts, he then cools the lens with cold water dripped on the chuck from a sponge and the lens is then ready for edging.

§131. Hand edging can be carried out satisfactorily with very simple apparatus. A rotating chuck carries the lens *L* (Fig. 27) and a brass plate *B* can be pressed up against the lens by means of a screw *S*. Carborundum mud is fed in between the lens edge and the brass plate as shown, and the diameter of the lens is measured from time to time until it is correct as measured by micrometer, or until the lens fits into its cell. Such a method, crude as it is, is appropriate for edging single lenses of high quality where the skilled man who made the lens is to be responsible for its completion. It entails little risk of splintering the edge or other accidents.

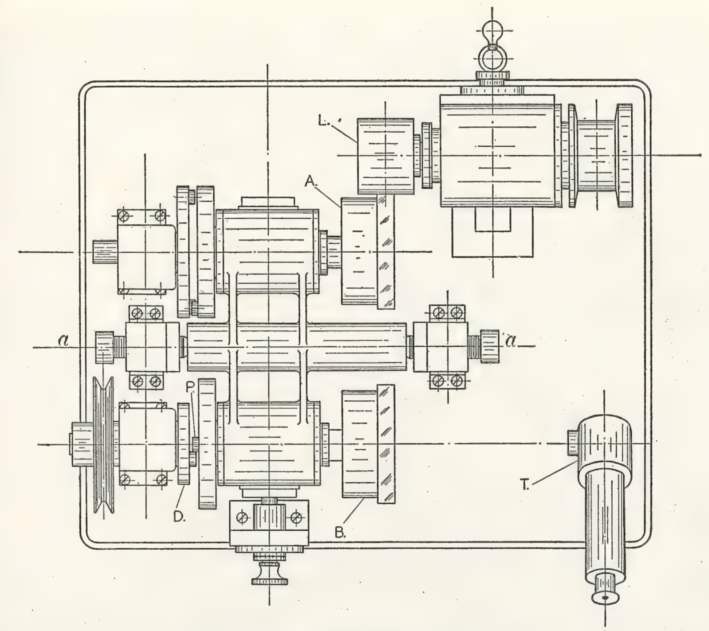


FIG. 29. Hilger Edging Machine.

§132. In the production of quantities of lenses special edging machines are, of course, in general use. Without referring to the machines used for edging spectacle lenses, which give excellent results for work of that kind, we may describe two special centring and edging machines.

A double spindle edging machine made by Adam Hilger, Ltd., is shown in Fig. 29. A machine of this type was shown to me at the Eastman Kodak Works in Rochester, U.S.A., by my friend Dr. C. E. K. Mees, now Vice-President of the Company, who very kindly gave me permission to copy it, and the copy made by Adam Hilger, Ltd., from my sketches has been in use from 1914 to the present time. The lenses are carried on two chucks *A* and *B* which can be interchanged by rotating them about a common axis *a-a*. When a lens is in the forward position a pin *P* on its bearing engages with a pin on the driving plate *D* which rotates it at a speed of about 120 revs. per minute. It is in this position that the centring is effected in the manner which was shown in Fig. 28. When the lens has been centred and cooled on its chuck, the lens positions are interchanged and the one which has just

been centred is brought into position for edging by the diamond lap V. It is rotated slowly and continues to edge while the operator affixes and centres a second lens. It is essential that the linear speed of the periphery of the lens during edging should not be too great.

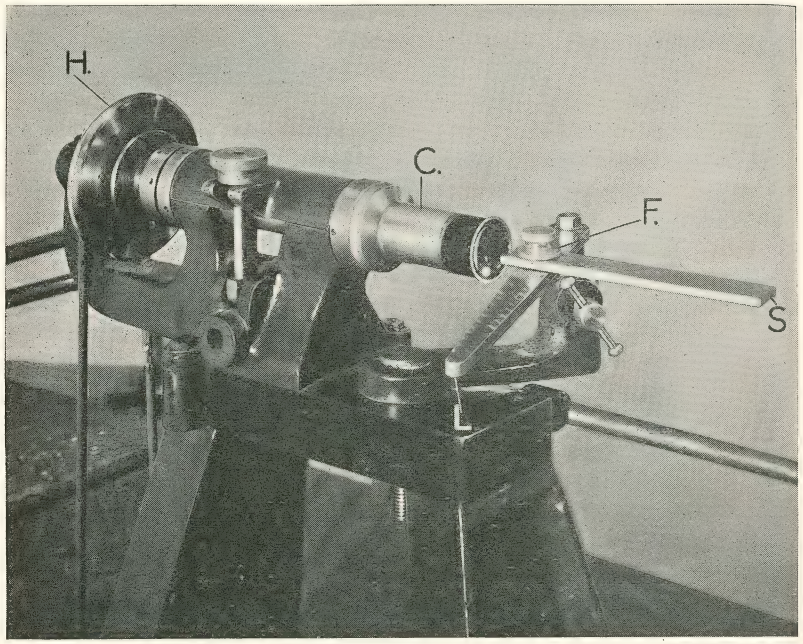


FIG. 30. Centring Lathe (Adcock & Shipley), with Hilger centring device.

§133. Another system of edging is embodied in the Centring Lathe and Edging Machine by Adcock & Shipley, shown in Figs. 30 and 31. The centring lathe consists of a simple rotating head *H*, with carrier spindle fitted with a chuck *C* as described above, and the centring is effected by means of an attachment added by myself which is a development of a device which has been in use for many years. A strip of hard wood *S* (box-wood for preference), is mounted so that it can rotate with friction, the friction being applied by felt washers *F*. This is brought gently up against the face of the lens while the pitch is still warm.

Two projections on the box-wood strip are thus pressed gently against the lens and if this is rotating eccentrically the other and longer end of the strip is caused to oscillate. If slight pressure is applied with the lever *L* this oscillation almost immediately dies away, the reaction of the strip with its friction being such as to set the lens central. The lens is then cooled off. This method is very successful with deep lenses

and if the chuck and lens are clean it is not necessary to check the centring by any optical device. The carrier chuck with its lens is then transferred to the edging machine (Fig. 31), the construction of which is as follows :

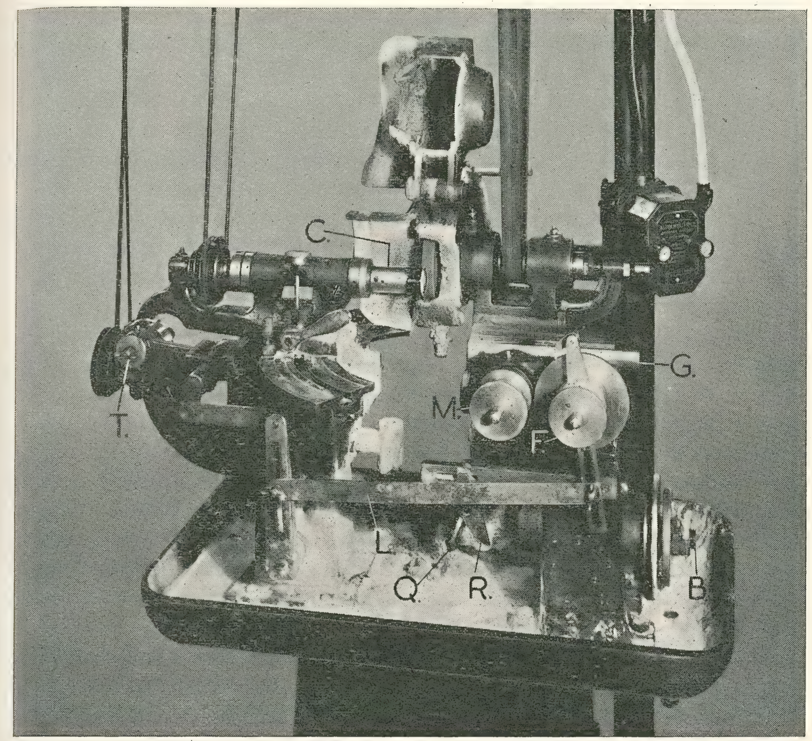


FIG. 31. Edging Machine. (Adcock & Shipley.)

Adcock and Shipley Edging Machine

§134. The grinding agent in this case is a carborundum wheel of suitable grit and grade (180 to 220, P. or Q.) rotating at 3500 r.p.m., across whose edge the centred lens oscillates along its own axis, while revolving. The grinding head complete pivots on the back shaft *B*, which also serves to bring the wheel into the correct position (see later) by a screw adjustment. On the front of the grinding head is a guide bar *G*, which, in the working position, bears on the right hand (feeder) stop point, which is itself brought slowly closer to the axis of the lens by means of the ratchet feed operated by the traverse crank *T* through the adjustable linkage *L*.

When the guide bar comes into contact with the fixed stop point attached to M the grinding ceases, since the forward motion of the wheel is arrested. The feed on the point F continues and retracts the bearing point clear of the bar. This serves as an indication that grinding has ceased.

The ratchet is then thrown out of action, and the feeder stop point rotated (clockwise) until the guide bar is clear of the fixed point M, by about 0·1 in., the whole machine turned off, the splash cover raised as in the illustration and the grinding head swung back until the bar Q catches in the restraining hook R. The lens is then measured for diameter, and if any reduction is necessary, the fixed point M is released from its clamping screw and the adjustment made.

When the lens is to size, the carrier spindle is removed and replaced by another on which is a lens ready centred, this having been prepared on the centring lathe (see §133) during the edging of the first lens. Before replacing the splash guard and switching on the machine, care should be taken to see that when the grinding head is released from the restraining hook R, and gently returned to the working position, the lens should clear the stone by a small amount. The splash guard is now replaced, the machine restarted and the lens left to edge. It is necessary that the lens should traverse right across the stone, clearing it at both extremities of stroke. This adjustment is obtained by setting the crank stroke (T) and grinding head traverse (B). While this proceeds automatically, the edged lens on the carrier spindle is replaced in the centring lathe and chamfered by holding a deep radius tool charged with medium emery against the lens, using an oscillatory motion to prevent too severe a local wear of the chamfering tool.

The lens and chuck are twice wiped with a moist sponge and the chuck then warmed with a Bunsen burner. It is essential to have a " blow-hole " or hot air escape in the wall of the chuck, otherwise the vapour pressure generated inside the chuck may cause the lens to drop off suddenly before the pitch has softened. When the lens starts to wobble slightly the chuck is arrested, the lens is removed and placed in a bath of turpentine, and the whole operation cycle recommenced with a fresh lens.

§135. Chamfers on Optical Work

While it is traditional at Hilgers to use very small chamfers on optical work, it does not appear that there is any valid reason for this except that it is evidence of careful work. As a reasonable chamfer for optical work intended for work of a more industrial character, the following specification has been adopted by us :

" Edges of all first quality optical work to have a chamfer whose width is 1/60th part of the longest surface terminating in that edge, with a minimum of $\frac{1}{2}$ mm."

Accuracy of Centring

§136. It has been found that each of the component lenses of an achromatic object glass of $1\frac{1}{4}$ in. diameter and 11 in. focal length should be centred to within one thousandth of an inch if the very finest definition is to be attained. If this limit is much exceeded the image of a star becomes perceptibly affected. A further point that requires attention is that the balsam layer must not be wedge-shaped. A variation in thickness of balsam from edge to edge of more than one thousandth of an inch should not be tolerated. It may be mentioned, however, that the method of balsaming in the oven described below ensures that this accuracy is attained automatically ; indeed, only gross carelessness could result in such an error, whatever method of balsaming is adopted.

Finally, in testing components of objectives of other focal lengths but of the same types, the tolerance of centring must remain the same if the full resolving power is to be maintained, namely the two components should have their optical axes coincident to within one-thousandth of an inch. This is most easily attained by centring each lens accurately in itself and then ensuring that their edges are exactly registered.

§137. Balsaming

Most achromatic objectives are cemented together by Canada balsam. Canada balsam, a resin obtained from the Douglas Pine, has as its chief constituents two separate resins and turpentine. The turpentine and other volatile constituents can be evaporated off by heating so as to obtain balsam of varying degrees of hardness. We use three kinds which we distinguish as hard, medium and soft. These degrees of hardness are defined as follows :

Hard : The standard test jig (see §48) sinks 5 mm. in $3\frac{1}{2}$ minutes at 20° C. The test is made by the pot containing the balsam being entirely immersed in water of this temperature for about an hour before test.

Medium : On this the standard jig falls 25 mm. in $3\frac{1}{2}$ minutes at 20° C.

Soft : This is obtained by passing the raw unclarified balsam of commerce through filter paper at 100° C. and heating it until it loses about 7 per cent. of its weight. The filtration is carried out in a steam-jacketed filter and the subsequent heating to produce the balsam of the various degrees of hardness is carried out as follows :

An old-fashioned pair of scales is used with the scale pan tinned (since iron discolours the balsam). The filtered balsam is put in the scale pan which is then heated from below to such a temperature that the balsam boils fairly vigorously. The temperature gradually rises

as the volatile constituents boil off but it should never be allowed to exceed 200° C. The loss of weight for the various degrees of hardness is as follows: soft balsam, 7 per cent.; medium balsam, 14 per cent.; hard balsam, 25·8 per cent.

If the hardening is carried out rapidly and in an atmosphere reasonably free from dust, the balsam remains clear and of a good light colour. On theoretical grounds it might be preferred to adopt a procedure which has been recommended to me, namely, to distil off the necessary amount of solvent by heating the balsam in a distilling flask under reduced pressure (7–10 mm. of mercury, which can be obtained with an ordinary filter pump) at a temperature of about 130° C.

§138. The Use of Soft Balsam

Perhaps the most usual process is to use soft balsam. This can now be purchased of excellent clear quality and very pale in colour so that there is little need for the optician to deal with the crude balsam as described above unless the consumption of the works is very large. A thick iron plate on three legs is heated from below by a ring burner. On the plate is placed a piece of paper and on this the lenses are placed, crown and flint side by side. The lenses being perfectly clean, they are brushed on the contact surfaces with a camel hair brush to remove dust, and the crown lens placed on the flint. Newton's rings should be seen, indicating that the lenses are nearly in contact. The crown lenses are lifted one by one by the finger and thumb of the left hand while with the right hand the worker puts a brass wire into the pot of balsam which is also on the hot plate, and with it transfers a drop of balsam to the upper surface of the flint lens. The top lens is then replaced and gently pressed down with a slight rotary movement by means of a cork, until the excess balsam is pressed out. The lenses are then allowed to cool down slowly and as they cool are pressed central with one another by the fingers so that when they are cold and the surplus balsam has been cleaned away the two edges are coincident. The balsam, however, is still quite soft and the lenses can easily be shifted relative to each other. It is necessary therefore to bake them.

§139. For this purpose they are put in an oven fitted with a thermometer and baked for sixty hours continuously at a temperature of 77° C. The oven is then allowed to cool before removing the lenses. The effect of this process is to harden the edge of the balsam and it will be found that, even after a number of years, if the lenses are taken apart all but a thin rim of the balsam round the edge is quite soft and sticky.

For certain purposes it is important that the lenses should be permanent in the sense that even if warmed they cannot readily be shifted relative to each other. This requires balsam so hard that any sudden shock may cause the lenses to split apart at the balsam layer. At this point it is worth mentioning that where conditions of great cold have to be met, such as in aircraft, all balsam is liable to split and it is generally considered therefore that it should be avoided. None the less, for certain purposes medium or even hard balsam is preferable to soft, and may be manipulated in the following way:

§140. Medium Balsam. The procedure is the same as with soft balsam except that the temperature of the hot plate requires to be higher so that the balsam is liquid enough to press out. No prolonged baking, however, is required, but in order to get the balsamed object glass free from strain it should be annealed in an oven for two hours at 40° C. and cooled not more than 3° every quarter of an hour. This procedure—which is on the careful side—is suitable for achromatic object glasses up to 3 in. in diameter. Lenses of $1\frac{1}{2}$ in. diameter and smaller can be dealt with much more rapidly.

§141. Hard Balsam. The procedure is the same as for medium balsam, except that the annealing should be carried out at 60° C. for two hours. Again the cooling for lenses of $1\frac{1}{2}$ in. to 3 in. should not exceed 3° every quarter of an hour, and again smaller lenses can be dealt with more rapidly.

§142. The Respective Merits of Hard, Medium and Soft Balsam

To sum up, one uses hard balsam when one wants to reduce the amount of shifting that can take place as much as possible. Unless the cemented components are stout the work should be annealed, otherwise the parts will be distorted. One uses medium balsam where the same effect is desired but where for some reason the temperature must not be raised too high, as in cementing Polaroid or gelatine filters between glass plates. Soft balsam is used where it is desired to avoid all strain, such as in the protection of half-wave plates of mica. Medium balsam is the most generally useful.

Hard balsam is in general to be preferred for small, medium for larger, and soft for large areas, since the mechanical strains introduced by differential expansion of large pieces are greater than those introduced by small pieces. If a soft balsam must be used, we prefer a hard balsam dissolved in Xylol, since it can be used without heat and baked at a low temperature. Although in general it has been regarded as dangerous to use cemented surfaces where very low temperatures are concerned, it has been found that prisms (of the same glass and small in size) if cemented with medium balsam and baked at 70° C. for $8\frac{1}{2}$ hours will stand a chilling test of $-50°$ C.

§143. Synthetic balsams have been made. For example, one is available having a refractive index for D of 1·65 in the soft condition and 1·8 when all the solvent has been volatilised. This is useful for

making certain polarising prisms, and is obtainable from Stafford Allen & Sons, Ltd., of 20 Wharf Road, London, N. 1, England, under the trade name of " Sirax ".

§144. Thickness of Balsam Layer

Since the refractive index of Canada Balsam is close to that of glass the reflections from the two contact surfaces are slight. It is, however, sufficient for Newton's interference fringes to be visible in light which consists of monochromatic radiations such as that from a low-pressure mercury vapour lamp. Observation of these fringes affords a convenient means of ascertaining the thickness of the cemented film. This is measured by observing the number of fringes which cross the patch of reflected monochromatic light when the object glass is tilted from a position of almost perpendicular reflection to a position at 45° to this. If m be the number of fringes the thickness is $6m \times 10^{-5}$ inches.

In a number of object glasses $1\frac{1}{2}$ in. diameter which were observed the thickness was observed to be 0·00025 in. and in some of 2·35 in. diameter it was found to average 0·00030 in.

Balsaming in Quantity. When numbers of object glasses require to be balsamed, it is convenient to adopt the following procedure. The lenses and medium balsam are placed on a sloping board drilled with holes, one hole being under each object glass. Metal pegs or nails are driven partly into the board near the holes in such positions that the lenses resting against them are centred with respect to the holes. The object glasses, together with the balsam, are put into the oven and raised to a sufficient temperature to make the balsam of the consistency of treacle, the object glasses having been first carefully cleaned, dusted and put in contact.

The board is then carefully removed from the oven and placed on a plate sufficiently warm to prevent the object glasses cooling down while the top lenses are lifted one by one, a drop of balsam put in the middle of the lower lens and the top lens replaced. This procedure can be carried out very quickly, since it is not necessary with this routine to press the balsam out.

They are then replaced in the oven which is brought to a temperature of 100° C. and the heat then turned off. The lenses will pass through the temperature of 40° C. slowly enough for the annealing to be good.

§145. Method of Determining at what Temperature to Anneal Balsamed Objects

At the same time that the objects are balsamed, balsam together two plates of glass about $\frac{1}{16}$ in. thick and the same diameter as the objects. Put these in water and heat slowly (say 3° every quarter of an hour) and try every few minutes whether one can be perceptibly slipped on

the other by sideways movement of the fingers. The temperature at which this can just be done is the temperature at which annealing may be carried out.

§146. Balsaming Prisms and Combinations of Prisms

From what has been said above it will be realised that no cement can be relied upon to hold cemented pieces in position relative to each other indefinitely, except at a temperature so low that the balsam is liable to split. The best that can be done if one must depend on the balsam alone is to use hard balsam and risk the splitting, which is not likely to occur in laboratory instruments which are not subject to rough usage.

Where possible, however, the cemented prism system should be held in metallic mounts which would geometrically hold the prisms in position even if there were no cement. An example may be given in the method of balsaming direct vision prisms where it is desired that the refracting edges of all the prisms should be strictly parallel, a desideratum which is important in, for example, the compensating prisms of Abbe Refractometers.

In this instrument two identical direct vision prisms are used in series and rotated in opposite directions. It is essential for the accuracy of the reading that the prisms should possess no deviation in a plane perpendicular to their dispersion. This condition is easily and accurately achieved by the use of the jig shown in Fig. 32. In this the

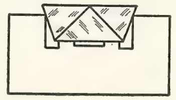


FIG. 32. Jig for Balsaming Compound Prisms.

prisms lie so as to fulfil the necessary condition accurately. If a small drop of balsam is placed between each of the surfaces, a small weight put on the top and the compound prism put in the oven as usual and heat treated as described above, the result will be satisfactory. The jig itself must be accurately machined so that the two upper edges are parallel to each other and to the lower surface on which the centre prism rests.

§147. Balsaming Gelatine Filters. Here the ruling condition is that the temperature should not be high enough to destroy the gelatine. It was customary with makers of high quality colour filters, consisting of a coloured gelatine cemented between glass flats, to use soft balsam and bake at a low temperature for five or six weeks. We have found, however, that in cases where it is desirable to use a harder balsam the following procedure is successful. A special balsam was used which

allowed the standard jig to fall 11 mm. in 1 minute at 20° C. The flats, after balsaming, were then heated to 84° C. in the oven for forty-five minutes and cooled at not more than 3° C. every quarter of an hour.

§148. It is convenient to stock balsams in different degrees of viscosity, since this enables one to cement complex prism systems in which one piece is cemented with the softer material to a combination of pieces which has previously been cemented with a harder one without shifting the former.

§149. Dermatitis Due to Cleaning Liquids.

Turpentine and turpentine substitutes are often used for cleaning off Canada balsam. It may be mentioned therefore that occasionally cases of dermatitis occur as a result of using various cleaning liquids. Turpentine and turpentine substitutes have on one occasion at least been the cause of quite a disturbing number of cases occurring at the same time. This was entirely got rid of within about a week by the simple process of washing the hands and arms in warm water prior to starting work and rubbing in, lightly, an ointment consisting of one part lanolin to two parts castor oil; this process of washing in warm water and rubbing in the ointment being repeated at the end of the day's work.

CHAPTER VII

MAKING AND WORKING BLOCKS OF PRISMS

Making Blocks of Prisms

§150. There are various ways of holding prisms in a block so that a number of them can be polished together. The one I have found most generally useful is the plaster block which I will now describe in detail.

A supply of Portland cement and of plaster of Paris should be obtained sufficient for a few weeks' working, and this should be kept in a dry place. The dryness is particularly important with the plaster of Paris, which is best kept in an enclosed box, say 6 ft. × 3 ft. × 3 ft., or, if the quantity is large, in a separate room, which is always maintained, by an electric heater or a sufficient number of electric lamps, at a temperature of at least some 5 or 10 degrees higher than the space outside the box or outside the room as the case may be.

§151. We will suppose that a block of pentagonal prisms is to be polished in a block 13 in. diameter (see Fig. 33). We will further suppose

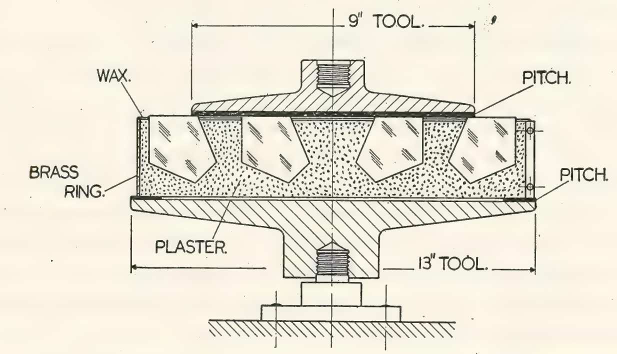


FIG. 33. Section of Plaster Block for Polishing Prisms.

that one of the surfaces has already been polished and protected with paraffin wax, and that each of the surfaces now to be polished has been carefully trued and smoothed accurately to angle with the already polished surface (for angling see §67). With the method of working now to be described, one can easily ensure that each of the surfaces polished in the block is accurately flat to within $\frac{1}{4}$ band on the proof plate and with very careful working the accuracy of each surface can be kept within $\frac{1}{10}$ band in which case the surface is good enough for most work without any retouching.

§152. The surface of the tool is cleaned and dusted and coated with paraffin wax of a kind which melts at about 60° C. The exact melting point of the wax is not a very important point. It is convenient to mark the tool first of all with a lead pencil in lines to assist in the regular arrangement of the prisms and economy of space, so that as many as possible are put in the block.

The tool is made hot enough to melt the wax, and each prism is carefully dusted on the underside and pressed down on the tool, to which it will adhere with an accuracy such that all the angles after polishing will be correct to within about 2 minutes if the trueing of each prism is good, *i.e.*, flat; a convex shape is obviously bad, especially where the prism is top-heavy, for the prism will then tend to tilt on settling down. The tool is then allowed to cool.

A brass ring about $\frac{1}{2}$ in. smaller in diameter than the tool is now put in position as shown,* the ring being kept from touching the tool by three brass slips about $\frac{1}{16}$ in. thick. This is to prevent the brass touching the polisher or smoothing tool when the prisms are being worked. The first layer of paraffin wax having set, a further quantity of paraffin wax should be poured in so as to make a layer of about $\frac{1}{10}$ in. thick; this is to prevent the plaster from coming into contact with the smoothing tool or polisher. One hour must be allowed to elapse for the cooling of the second layer of wax before the next process, putting in the plaster.

§153. A sufficient quantity of the plaster mixture in the proportions of 4 of Portland cement to 1 of plaster of Paris is mixed very carefully and thoroughly so as to be uniform, using a bricklayer's trowel for the purpose. The powder is then spread on a board in a heap with a depression in the middle, and water poured, a small quantity at a time, into the depression, the outer parts of the heap being scattered on top with the trowel just as in mixing concrete; as the heap becomes moistened throughout, the process of scattering the dry powder should be changed to one of chopping the moistened plaster with the edge of the trowel and turning it over until a lump uniformly moist is produced of about the consistency of mortar as used by a bricklayer.

The operator then puts on a pair of rubber gloves, which are desirable for cleanliness and also to avoid irritation of the skin which can be caused by Portland cement, and taking portions of the mortar in the fingers thrusts them and presses them into the interstices between the prisms in much the same way as one forces the stuffing into a chicken or turkey. The block is filled right to the top of, but not above the brass ring, with plaster (see Fig. 33) which is made to settle down snugly about the prisms by patting, when, in the same way as wet sand does, it becomes wet and fluid. A block so prepared with the minimum of water to produce a

* Although at the stage shown in Fig. 33 the block has been completed and inverted.

workable mortar will dry out in 36 hours when the block can be removed from the tool by heating the latter.

Next stick the block with a ring of pitch on an iron tool similar to the one on which the prisms were assembled. Such a block of prisms, with the polisher in position, is shown in Fig. 33. If the block of prisms is 13 in. diameter the polisher should be about 9 in. diameter.

Removing the Prisms from the Plaster Block after polishing

§154. The brass ring having been removed, the block can be broken up by blows from a hammer on the back of the block, or by a hammer and cold chisel. The breakage of the block will often occur along one of the surfaces of the prisms and those prisms which are so uncovered can often be removed forthwith almost free from plaster. There is no difficulty in removing any small pieces of plaster still adhering to the prisms.

It is convenient, by-the-bye, to stock paraffin wax of different melting points, since this enables one to perform composite operations in which one piece is cemented with a softer wax to a combination of pieces which has previously been cemented with a harder wax. The same applies to the advantages of having available hard, medium and soft Canada balsam.

§155. Polishing Blocks of Prisms on Accurate Metal Jigs

This method of polishing blocks of prisms is applicable where sufficient numbers of the same kind of prism have to be made to justify the expensive type of tool required. It was introduced by me about 1915 to polish the diamond-shaped surfaces of the roof prisms which in many modern instruments serve the double purpose of inverting the image of an object and of turning the path of the rays through a right angle. There is no need to describe these well-known prisms. The roof edge is at 45° to the diamond-shaped end faces, while each of the two reflecting surfaces makes an angle of 60° with the last-named surfaces. In order that the prism may give good results, the "roof" surfaces require to be perpendicular to each other to within a second, but the diamond-shaped faces may be several minutes out. With highly skilled workers this roof angle can with advantage be finished before working the diamond faces, but there is great risk of marking the surfaces in the subsequent processes, so in general it is preferable to leave the final correction of the roof surfaces till last of all. An accurate steel jig is made consisting of a flat optical tool A (see Fig. 34) and a number of strips with interior surfaces B, B, etc., accurately at 90° to each other and at 60° to the surface of the tool. The parts of this tool and its assembly must be accurate to within 1 minute. The figure shows a number of prisms in position.

Rectangular strips of glass are made, two adjacent surfaces of which constitute the roof. These strips rest in the angular recesses with their

lower ends bearing on metal strips whose function it is to set all the prism faces at the correct height, thus ensuring the same length of prism throughout the block. The tool is then placed in the trough

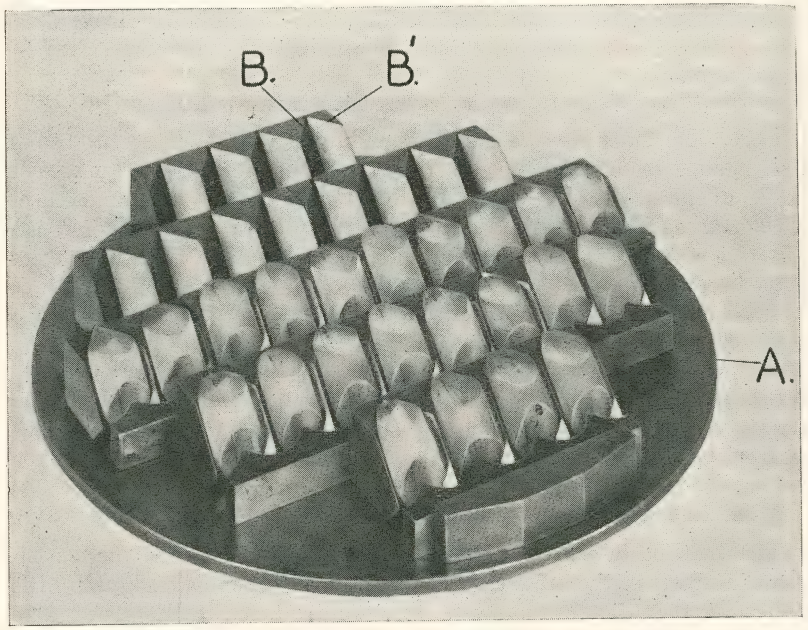


Fig. 34. Accurate Metal Blocking Jig.

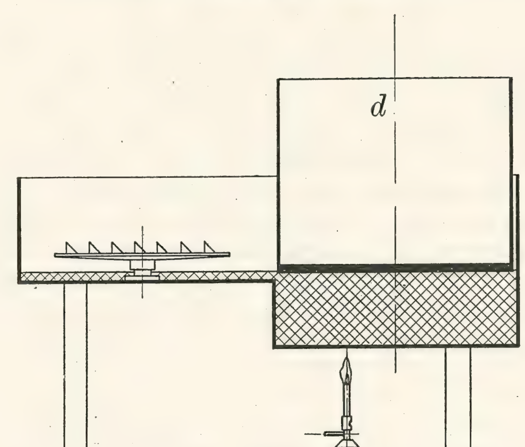


Fig. 34*a*. Paraffin-wax Trough for blocking prisms.

shown in Fig. 34*a*. This consists of a deep cylindrical portion *d*, the lower part of which is filled with melted paraffin wax, while the upper is filled with a hollow drum which is supported on a long screw about $\frac{3}{8}$ in. diameter attached to the bottom of the trough. When the drum is screwed down it causes the melted wax to flow into the side trough in which is the block of prisms. The wax is melted by heat applied from

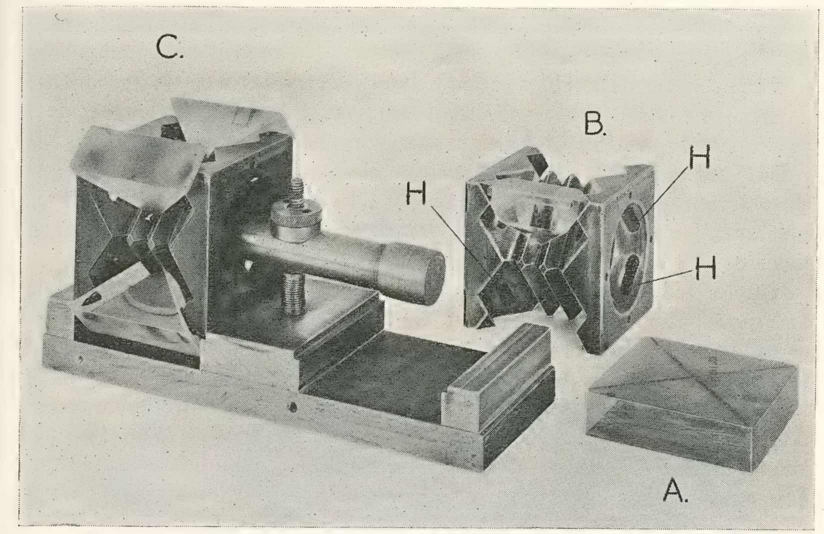


Fig. 35. Jigs for making Roof Prisms.

below and this, of course, has the effect also of heating up the tool with its charge of prisms. When a sufficient time has elapsed for the tool and prisms to become thoroughly warm, the drum *d* is screwed down and this may be done fairly rapidly. This forces the wax to rise until the tool, with its prisms, is completely immersed and, after leaving for, say, 5 minutes, the drum is screwed up again and the tool with its prisms allowed to drain and cool.

If these operations are carefully performed, the prisms will not move more than about 2 minutes, so that when the block is polished so that the top surface of the prisms is parallel to the tool, all the polished surfaces will be correctly to angle with the right-angle faces to within about $3\frac{1}{2}$ to 5 minutes. This accuracy is sufficient for most purposes for which these prisms are required.

A Way of making Roof Prisms used in one of the Optical Shops of Adam Hilger, Ltd.

§156. We have at different times used a number of different ways of working roof prisms. The following has been found appropriate for

use by previously untrained women workers, and is a further illustration of the use of accurate metal jigs.

The prisms are to be of 1 in. aperture. Moulded slabs of boro-silicate crown approximately $3\frac{1}{4}$ in. square and $1\frac{1}{4}$ in. thick are slab milled to a thickness of 1·02 inch.

The slabs are slit across the diagonals to give 4 prisms, as shown by the lines in Fig. 35*a*.

Each prism is then put in a jig and the cathetus faces are machine milled on the glass milling machine.

The prisms are then blocked in plaster and the cathetus faces polished.

The prisms are now ready for roofing, which is done in an accurate jig, Fig. 35*b*, in the form of a cube, preferably in aluminium. The prisms are mounted with shellac at each of the four corners of the jig as shown in the figure, which shows one prism in position. With this method of mounting an accuracy between the cathetus and roof surfaces of ± 3 minutes can be assured.

The loaded jigs are now clamped, two at a time, on a holder as shown in Fig. 35*c* (in which one only of the two jigs is shown). This holder is clamped on the bed of the milling machine and each of the four sides of the cube becomes in turn a base for a cut to be taken from the top side, the jig being rotated through 90° for the successive faces to be milled.

The roof faces are then smoothed and polished to the requisite accuracy while still in the jig, measurements of angle being made in the first instance by the Angle Dekkor (see §182), and then by the Hilger N.26 Interferometer. There are holes, H, H, in the jig, by means of which observation can be made on the Angle Dekkor or Interferometer by internal reflection at the roof of each prism.

Protectors are used for supporting the dividing line of the roof. The surplus of the height noted at the beginning of this section is used to equalise the widths of the roof faces when that is necessary.

The prisms are finished by milling in accordance with whatever method of mounting the prisms is adopted in the instrument.

§157. Polishing Blocks of Prisms held in the Block with Waxed Felt

This alternative method is sometimes advantageous. It is necessary to have a formed tool but it need not be accurately machined. Taking the case of blocking pentagonal prisms, one first of all chamfers all the edges of the prisms which it is presumed have been trued to angle. They are then blocked in the shaped holder (see Fig. 36) as follows: A flat tool is heated and smeared over with paraffin wax, the tool being of such a temperature that the paraffin wax runs like water. The prisms are then formed up in rows allowing a suitable separation between each prism to correspond with the formed holder. The prisms should be pressed as close down to the tool as possible and the whole then allowed

to cool. The faces that have to bear on the felts should be smeared with paraffin wax to protect them.

While this operation is in progress, heat in a saucepan cement consisting of three parts of rosin and one of beeswax. Dip into this melted cement pieces of felt, and when they have done bubbling place the pieces of cement on the cold former, so that when the prisms are in position they will be held on two faces.

The prisms having cooled, the tool holding them is inverted and the prisms and tool lowered on to the felts. The formed holder is then heated until cement drips off it, then allowed to cool. The block is then ready for smoothing and polishing in the ordinary way.

The prisms can be knocked off with a smart tap applied through the intermediary of a piece of wood, but to avoid the prisms being knocked together a piece of card should be placed between the prism which is being detached and the one next to it.

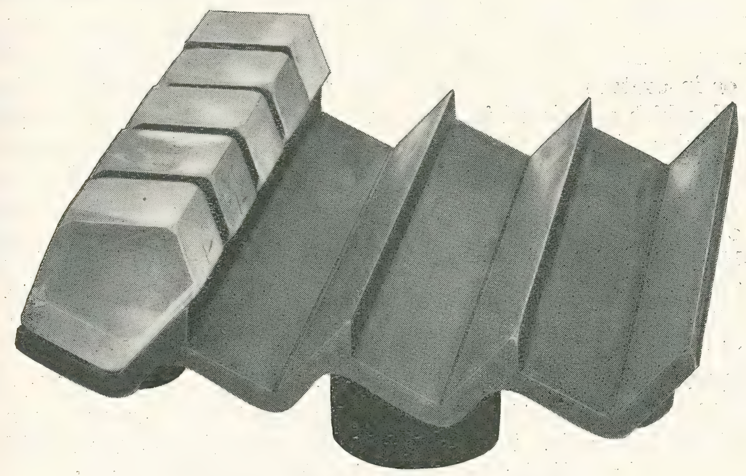


FIG. 36. Blocking with Waxed Felt.

§158. Polishing Blocks of Plane Parallel Glasses

Plane parallel glasses are often made from plate glass, in which case nothing is required prior to blocking but to edge the glasses to shape. If they are to be made from blocks of glass, the slitting, roughing and trueing to thickness and mechanical parallelism are first carried out and the discs then blocked for polishing the first side.

The method we prefer for this is to block them on pitch. This should be poured on a tool as in making a polisher but the pitch should be $\frac{1}{2}$ in. thick. It should be flattened as in making a polisher. Then the tool is turned upside down while still warm (but not too warm) and allowed to sink on the plates (laid on a flat tool) and cooled. One side

having been polished in this way, a flat optical tool which has been polished is taken and the glasses laid thereon, having first been carefully dusted. It is desirable that this tool should be of glass, and the same kind of glass as that to be polished. If it is of a different kind of glass, appreciable distortion may take place owing to difference of expansion and as a result imperfect surfaces will be produced. By saying that the tool should be of glass I mean that a plate of glass about $1\frac{1}{4}$ in. thick is fixed to the ordinary cast-iron tool by means of a layer of pitch, the glass then being smoothed and polished. The tool must be carefully tested to see that it is thoroughly flat, since even a slight departure from flatness may mean that the edges are tilted by a material amount relative to the middle of the tool. It is customary to make plates of this type from plate glass so that the top surface, having its original polish, permits one to see the Newton's fringes due to interference between the tool and the undersides of the plates. It is best to perform this operation in a dust-free enclosure, at least when the work is being done by other than skilled operatives, since the whole precision of the method depends on the under surfaces of the plates being parallel to or in contact with the tool. One then scrapes paraffin wax into shreds which are placed in between the plates, and on slowly heating the whole tool the wax melts and spreads in a thin film underneath the plates, between them and the tool. The tool is then allowed to cool slowly and the top surface ground and polished parallel to the tool. In order to ensure that the top surfaces are parallel to the tool, an Angle Dekkor (§182 *et seq.*) may be used to obtain reflection from a glass plate put on top and a small space cleansed of paraffin wax in the under tool, or alternatively a depth gauge may be used on the opposite sides of the tool.

§159. Plane parallel plates, say $2\frac{1}{4}$ in. diameter and $\frac{1}{4}$ in. thick, can be laid down on a tool by carefully working in this way to an accuracy of about 5 seconds. The chief error in parallelism in the resulting windows will usually be determined by the following factors:

(1) Lack of flatness of the tool on which the plates are blocked. Supposing one is working with three flat tools, A, B and C, they can be rubbed together in three combinations AB, AC, and BC. Supposing they have been ground together until they almost fit, the three combinations will then comply with one of the following conditions:

(i) All three fit.
(ii) Two fit, the third swings.
(iii) Two fit, the third binds.
(iv) One fits, two swing.
(v) One fits, one swings, one binds.
(vi) One fits, two bind.
(vii) Three swing.
(viii) Two swing, one binds.
(ix) One swings, two bind.
(x) All bind.

The closeness of approach to contact may be easily estimated by use of tinfoil, which is available in leaves 0·0005 in. thick, of remarkable consistency. If a pair of tools are known to swing about the middle, and three small pieces of foil placed symmetrically round the periphery of the lower tool are sufficient to annul the tendency to swing about the middle, then the tools are in contact to within this limit (0·0005 in.). If the tools bind at the edge, a small piece of tinfoil is placed in the centre of the lower tool, and if this makes them swing about the centre then again the tools are in contact to this limit. Calculation shows that in only two of these cases can the lack of flatness of any surface be greater than $3t/2$, where t is the thickness of the tinfoil used in the test, these cases being Nos. (viii) and (ix) above. In no other case can it be greater than $t/2$.

If all three combinations of the three tools pass these tests with tin foil 0·0005 in. thick, then we can be certain that all the tools are flat to 0·00075 in. A 9 in. tool with a sagitta of 0·00075 in. has a radius of curvature of 1125 feet and a slope at one inch from the edge of the block of 54 seconds relative to the average surface.

(2) The error that can arise from the surfaces not being polished quite flat. The sagitta (or sag) of a spherical but nearly flat surface varies as the square of the diameter. Thus, if a 2 in. diameter proof plate applied to the block shows that the surface is $2\frac{1}{2}$ Newton's rings out of flat, the 9 in. diameter block will be 50 rings out of flat ($=0·0005$ in.). This indicates a radius of curvature of approximately 1300 ft. and an inclination to the average surface in a position 1 inch from the edge of the block amounting to 40 seconds.

This error must be added to or subtracted from that due to lack of flatness of the blocking tool according to the sign of curvature of each. A large test plate is therefore useful, large enough to cover at least half the block. If the wax is cleaned from a central area of the blocking tool, enabling a reflection to be obtained therefrom, the Angle Dekkor may be used to measure the (mean) error of parallelism to an accuracy of about 10 seconds.

Since the errors referred to above are those that can easily occur in ordinary working it will be seen that errors of parallelism may occur up to $54+40+10=104$ seconds $=1'\,44''$ unless care is taken to get the tools flat to a higher accuracy, using a large test plate; and in that case a more severe mechanical test can be obtained by using thin plates of mica instead of tinfoil. If the measurement of parallelism be made not by the Angle Dekkor but by an interferoscope, the parallelism can be measured and corrected to within 1 second of arc.

To sum up, in order to produce block work of a high order of parallelism, say 30 seconds, it is necessary not only to observe the most scrupulous care in sticking the plates down, but also to ensure that the blocking tool, smoothing tool or tools, and the polisher forming tool,

are flat to a very high order of accuracy, and to provide an interferoscope for checking the parallelism.

Plates of glass can be laid down on a glass tool and fixed by wax as described above to an accuracy of about 4 seconds. The Angle Dekkor enables the top surface to be controlled to within about 10 seconds. It is therefore worth while devoting a good deal of care to getting the tools flat and in contact. If they are corrected and the surface polished flat enough to result in a 35 second error, the procedure would assure a parallelism to within about 50 seconds, or if meticulous care were taken to get the tools in contact and flat, one might get down to 30 seconds accuracy straight from the block. A slight increase in parallelism may be obtained by using an Interferoscope (para. 189) instead of the Angle Dekkor, and I have designed a small portable interferoscope which can be used without moving the blocks from the machine.

CHAPTER VIII

THE TESTING OF OPTICAL WORK

§160. Surface Marks

A lens or prism should be well polished, and free from bubbles and other defects in the glass, scratches and other surface marks. Faults such as these are detected by simple inspection, the lens being held in a strong light, from which the examiner's eyes are screened, and with a dark background.

The surface defects occurring in optical glass work may be due to :

A. Scratches occurring in the roughing or trueing process not removed by the smoothing.

B. Deep grey left from the early grades of emery ; this can be distinguished by being coarser than *C*.

C. Uniform fine grey due to insufficient polishing.

D. Sleeks. These are strong at one end and trail away to vanishing point at the other end. They are usually due to the polishing pitch being too hard for the temperature of the shop. Hence, if the shop is very cold in the morning, there is no harm in gently warming the polishers provided they are formed again on the true tool.

E. Polishing marks caused by the polisher not fitting in good contact with the work. This happens especially when fresh rouge is applied, and for this reason, during the last half hour of polishing, no fresh rouge should be applied—only enough water to keep the surface moist.

F. Marks made by using the test plate, which always result from insufficient care in cleaning and dusting the test plate or glass to be tested. Everyone who uses the test plate must be provided with a tin box with loose fitting lid and camel-hair brush inserted in the lid. Inside the box is kept an old linen handkerchief which has been boiled in distilled water. This must always be kept in the box when not in use and never on any account be laid down on the bench, unless the latter has been wiped clean of all dust.

G. Marks occurring in the cleaning owing to gritty material on the cleaning rags. For this reason everyone should keep a special supply of clean rag in an enamel kitchen canister. The rag should never be put on a dirty or dusty bench and must always be replaced in the canister with the lid on when not in use.

H. Marks due to various special means of blocking the glass work ; for example, one method of holding in position a number of pieces of glass to be polished in a block is to attach them to an iron holder by means of pieces of felt which have been steeped in hot wax (see §157). If there is grit in such waxed felt it may cause digs in the surface.

The avoidance of conditions likely to cause surface marks is dealt with in §126.

Marks are not excusable when work is in the hands of skilled men, but they are the chief cause of low output when the work is being done by unskilled workers.

For this reason, in times of crisis, when output is imperative and the use of unskilled labour unavoidable, it is important that the greatest leniency should be authorised and exercised by the inspectors. Finished work of the utmost optical perfection is often rejected, by official or unofficial inspectors, for surface marks which would cause no defect whatever in the finished instrument, by reason of rigid insistence on an aesthetic degree of perfection which has been achieved in tranquil times.

It is stated that Fraunhofer, when one of his customers complained that an achromatic objective had surface defects, replied that he made his objectives to look through, not at.

§161. Tests concerning Definition

The defects which affect the definition of the images formed by a lens, prism, mirror, or plane parallel glass, are more important.

It must be said at the outset that among the tests applied during making and on completion, there is one that can rarely with safety be omitted by the optician who wishes to maintain a reputation for good work, and that is to try the work exactly as it is intended to be used.

But in addition to this he should also apply tests more severe than any which the lens will be subjected to in use, and these should include tests which will tell him not only whether the work is faulty or no, but if defects are present will give him at least an approximate measure of its badness and an indication of the origin of its faults.

§162. Spectacle lenses, condensers and lenses for magnifiers and eyepieces are made in large quantities and sold without any test at all being made, except to reveal such faults as might be readily perceived by a purchaser, and the accuracy required for such lenses is such that where manufacture is carefully controlled it is rare that any lens of these kinds gets into use that is not amply good enough for the unexacting requirements.

§163. The Star Test

To deal first with telescope objectives, a good test is provided by examination of a star, or of an artificial star produced by a distant ball of black glass, or a bulb of mercury, in which the sun is reflected.

Actually, if the wave theory of light is taken into account, calculation shows that the image formed by a telescope lens is not a point, but a disc of finite diameter surrounded by rings of rapidly decreasing intensity.

Examination of the image with a lens of high enough power confirms the result of calculation—indeed Herschel knew and used this phenomenon in testing his object glasses long before any explanation of it was given (Foucault (1858, 1859).

Examination of these rings, particularly as they appear a little within and without focus, can yield with experience most valuable information concerning any faults that may be present ; and this method of test has been applied with excellent results by Dennis Taylor (1921).

§164. The best description which I know of the various appearances seen in a telescope when a star is examined is to be found in a book by Mr. H. Dennis Taylor, *The Adjustment and Testing of Telescope Objectives*, 1921, T. Cooke and Sons Ltd., Buckingham Works, York. The first edition was published in 1891 but the following extracts are quoted from the 1921 edition with the permission of Messrs. Cooke, Troughton and Simms (the present owners of the copyright).

“ The least experienced of observers will have noticed that the luminous disc visible when a star is thrown out of focus is not of continuous brightness, but is broken up into a system of interference rings ; the farther out of focus and the larger the luminous disc the greater is the number of rings visible.

“ Squaring On”

“ **§165.** The operation called squaring-on means the adjustment of the optical axis of the objective until it passes accurately through the centre of the eyepiece. The symptoms resulting from any such maladjustment of the objective are strikingly evident if the objective is tilted to any very serious extent ; but if only to a very slight extent, then the observer will need very careful and discriminating exercise of his eyesight in order to give the final touches to the adjustment. It must be remembered also that an objective must be carefully squared-on before the observer is in a position to form a just estimate of the quality of the glass unless it is a very bad one ; for there is no type of object glass in existence which will give a perfect image of a point of light or star at a point situated even $\frac{1}{2}$ a degree only from the optic axis. In the first place the oblique image is never a round star disc but a sort of linear formation caused by the astigmatism which marks the oblique performance of refractors and reflectors, but besides this inevitable astigmatism there is also an oblique effect known as coma or eccentric flare whose amount very essentially depends on the form of the object glass. This defect is superimposed upon the inevitable astigmatism and in many cases is violent enough to completely disguise the latter.”

The author then describes the different effects observed as a result of faulty squaring-on with different types of telescope object glass and the procedure by which the operation of squaring-on is to be performed.

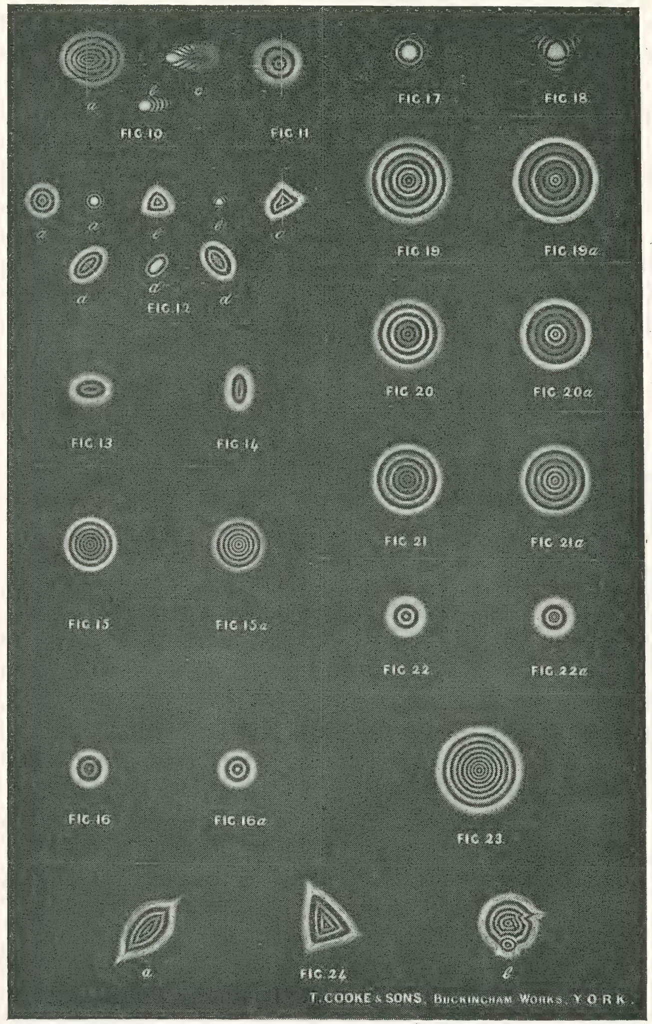


PLATE I

With telescopes of less than three inches aperture it is to be expected that the maker will provide a cell and mounting sufficiently accurate to obviate the necessity for means of adjustment, but with larger objectives adjusting screws should be provided by the maker whereby the cell can

be tilted in any direction. The appearances concerned with squaring-on are shown in Plate I, Figures 10*a*, 10*b* and 10*c*.

The first type considered by the author can take several forms, all of which are characterised by good correction for spherical aberration but inward coma, or coma in which the flare lies inwards towards the optic axis.

"When such an objective has been finally adjusted (squared-on), it will be found on examining the image of a small star that the luminous disc or ring system will expand itself concentrically with regard to the position of the star when in focus as in Figs. 12, *a*, *b*, *c*, *d* and d_1, Plate I, where a little cross marks the position of the star when in focus. This point is the only one to be regarded at present, for it may be found that although the luminous disc expands itself concentrically with regard to the focused image, nevertheless the disc is not round but oval (d and d_1) or even of some irregular shape, *c*. Such appearances indicate defects either in the objective or in the eye of the observer or both."

Astigmatism

(The following is abstracted from pages 30-39 of the book referred to)

§166. The effect of astigmatism is the formation of a short focal line in one plane on one side of the focus and a similar line, but at a direction at right angles to the first on the other side of the focus. Hence the image of a star, instead of being a minute round disc like 12a', may show either as an elongated line in one plane or a similar line at right angles to the former on the other side of focus. Fig. 12d'' represents such an elongated star image. The cross-section of the rays half-way between these two focal lines will be a circle whose diameter is equal to half the length of either of the two focal lines. This is the circle of least confusion and will in practice be the point actually focused upon. At other positions the image appears an oval, Figs. 13 and 14, Plate I.

In order to determine whether the astigmatism is due to the telescope or to the observer's eye the former can be rotated in its mounting. If the focal lines rotate with it then it is the telescope which is at fault.

Spherical and Zonal Aberration

§167. Any well-marked aberration can best be detected by racking the telescope sufficiently out of focus to cause three or four diffraction rings to be visible. If within focus it is found that the central rings look very feeble and the edge rings, and especially the outermost one, look massive and luminous then the inference is that the edge rays fall short or come to focus nearer to the objective than the focus for the central rays, in other words there is positive aberration. Plate I, Fig. 15, represents the appearance within focus in this case and Fig. 15*a* the complementary appearance outside focus.

The author describes these appearances and other similar ones resulting from zonal aberration in great detail, and the reader who follows out his description with a few actual telescopes will find that a very great deal of information can be obtained as to the performance, defects and causes of any defects in the telescope. The extra focal method of test described by the author is a very useful one indeed.

Perfect Figure

§168. If all the conditions necessary to perfection are fulfilled in an objective it will be found that the ring systems which are observed when a bright star is thrown out of focus are perfectly circular in outline while the individual rings grow gradually and regularly stronger and further apart as the outside ring is approached, this outer ring running a little out of proportion in its brightness and breadth. Above all, the appearance and arrangement of the rings should be exactly the same on both sides of focus, if allowance is made for the blue flare which somewhat enhances the brightness of and disguises the more central rings when outside focus.

Artificial Star

§169. Mr. Dennis Taylor is describing the appearances seen when a telescope is directed under favourable atmospheric conditions at an actual star. The telescopes of small size used in most optical instruments cannot wait for their test until time and climatic conditions permit such a test to be used in production. Nothing is quite so good as an actual star but a sufficiently good test can be provided by placing at the focus of a collimating lens of good quality a piece of tinfoil in which a number of holes have been made in the following way. Thin tinfoil, say 0·0005 in., must be used. It must be laid flat on a backing which is neither glass-hard nor soft—ebonite is about of a favourable consistency—and a needle, previously sharpened with great care to a real point as seen by a magnifier, very lightly jabbed down on to the tinfoil a number of times with different degrees of light force. With luck and perseverance one will be able with such a piece of tinfoil to find a star which while permitting sufficient light to pass through has dimensions small enough to be considered a point for practical purposes.

The selected hole is illuminated with the image of a Pointolite lamp.

Optical Testing Bench

§170. Such a collimator is embodied in an optical testing bench which has seen continuous service for over thirty years in the optical testing room at Hilger's. It is shown in Fig 37. The artificial star or other test object, S, is attached to the end of the collimator C, in the focus of a 5 in. achromatic objective O. A telescope T rotates on a sub-

stantial axis A, the bottom end of which is supported on a ball-bearing sunk into the cement floor. In this manner the telescope can be swung either into alignment with the collimator or to make any desired angle with it. In this way it can be used for testing prisms of any shape such

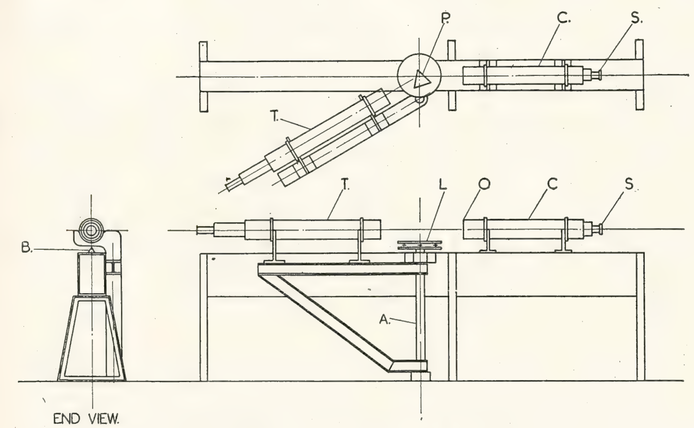


FIG. 37. Optical Testing Bench.

as a 60° prism, P (shown in the plan) which stands on the levelling table L. The end view shows a triangular bar, B, on which can be mounted a variety of stands for eyepieces, a microscope, or mounts for lenses which require testing.

Filling the Aperture

§171. In order to get a proper test of an object glass it is essential that light from the object should be received by every part of the object glass, under an arrangement known as "filling the aperture". In looking at a natural object this occurs as a matter of course, but when one illuminates a hole such as that described above, or the slit of a spectroscope, by means of a local light source the image of which is focused on the hole or slit, it may be that the condensing lens is so defective or the light source so out of line that the aperture of the lens is not filled. This can be easily observed by removing the eyepiece and putting the eye in its place, when it will at once be seen whether the aperture is filled or not.

§172. Another test which is highly informative is that of Foucault (1858, 1859 *a* and *b*) (adopted also later for other purposes by Toepler (1866, 1867)). In this test, often called the "Schlieren" test, the object glass is examined without any eyepiece. Placing one eye in the focus of a star (or artificial star) one sees the object glass uniformly illuminated.

If one then passes a knife edge slowly across the focus from right to left, this uniform illumination disappears over the whole area of the object glass simultaneously if, and only if, the rays all pass accurately through the focus. If they do not, the object glass first becomes darkened in appearance over those regions from which rays pass to right of the focus. Foucault's test affords direct evidence of the course of the rays from different parts of the object glass.

§173. Still fuller knowledge of the course of the rays is to be had from Hartmann's method (1904). In this, a diaphragm pierced with holes, is placed close to the object glass, and the image of a star photographed within and without focus. Such photographs consist of dots, each of which corresponds to one of the apertures in the diaphragm ; and from the distance apart of the dots in the two photographs can very simply be deduced the course taken by the rays from the corresponding parts of the object glass. Highly accurate results have been obtained by this method, but it is very laborious.

§174. In quite a different category from the above are the methods of examination founded by Twyman and Green (1916, 1918, 1923) on the interferometer of Michelson, to which a separate chapter is given.

§175. Methods which may be of value in special cases have been developed by Waetzmann (Bratke 1924) (founded on the Jamin refractometer), Ronchi (1926), and Lenouvel (1924). These last two are derived from Foucault's test.

METHODS OF TEST FOUND MOST USEFUL IN THE OPTICAL WORKSHOPS OF ADAM HILGER, LTD.

Testing Surfaces ; the Proof Plate

§176. If a shallow convex glass surface is laid on a flat one a system of rings is seen around the point of contact. These are called "Newton's rings". When two flat surfaces are put together, the one being very slightly inclined to the other, the colours are not arranged in rings but in more or less parallel lines or curves, and they are then called "Newton's bands". Although others had observed that transparent substances when made very thin by being blown into bubbles or otherwise exhibit colours according to their thickness, it was Newton (*Opticks*, Book II) who first found a relation between these colours and the corresponding thicknesses.

The thickness of the film of air at any point of such a system of rings or fringes can easily be determined by the colour at that point, or, better, by counting the number of bands from the point of contact. Near the point of contact, where the plates are very near together, the colours are brilliant, and up to four or five rings or bands one can assume that the increase of thickness from one band to another is about 1/100,000 ins. Beyond this the fringes gradually become fainter unless monochromatic

light such as is provided by a low pressure mercury vapour lamp is used.

§177. Accurate plates, whether flat or curved, which are used for the purpose of testing surfaces which should fit them are known as test plates or proof plates. They may be used either in comparing a surface with one of assured flatness, or for ascertaining whether a surface has a desired radius by the use of a proof plate of the same radius but opposite curvature.

These plates have been used for many years ; they are best made of quartz, since they then last much longer without getting scratched. Wherever a number of identical lenses are to be made, proof plates, or proof spheres as they are sometimes called, should be made to correspond exactly to the forming tool ; they are not only needed to test the surfaces of the lenses, but also to ensure that in the course of time the true tools do not depart from their nominal curvature, for such tools are liable to alter gradually in curvature owing to wear.

§178. When the test plate is put in contact with the lens or flat surface to be tested, great care should be exercised to see that both the surfaces in contact are perfectly clean.

This should be effected, first by thoroughly cleaning both surfaces by means of methylated spirits or other similar cleansing solution free from grease. Then, before laying the test plate in contact with the lens, a camel-hair brush should be used to flick away any particle of dust which may float on to the surface during this operation.

Care should be taken to avoid prolonged handling of the lens and test plate and thus causing distortion of the surface by heat. Before finally judging the quality of the surface by the appearance of the coloured Newton's Rings, time should be allowed to ensure that the test plate and lens have both acquired the same temperature—a lens or plate of 2 in. diameter may take five minutes to settle down. If only one colour is seen over the contact surface, this area of the lens or block of lenses is correctly polished.

§179. If uniform circular rings or colour bands appear most brilliantly near the periphery of the test plate, contact is towards the outside ; whereas if the brilliant bands are in the central area contact is in that area.

§180. Although white light is often employed for observing the fringes, yet in the workshop it is desirable to have ample illumination by sources of monochromatic illumination. The most generally useful is the low pressure mercury vapour lamp ; a neon lamp is also good and is conveniently portable. One can then see many more fringes and this reduces the temptation, when the two surfaces do not readily come into contact, to press them forcibly together in order that the fringes seen by white light may be distinct and of the brilliant coloration which makes the test a severe one. Such failure of the surfaces to come into contact

is always due to dust or dirt of some kind and the optician, in attempting to bring together by pressure surfaces which are not thoroughly dust free and clean, may produce scratches requiring the re-smoothing of the polished surface.

1 2 3 4 5 6

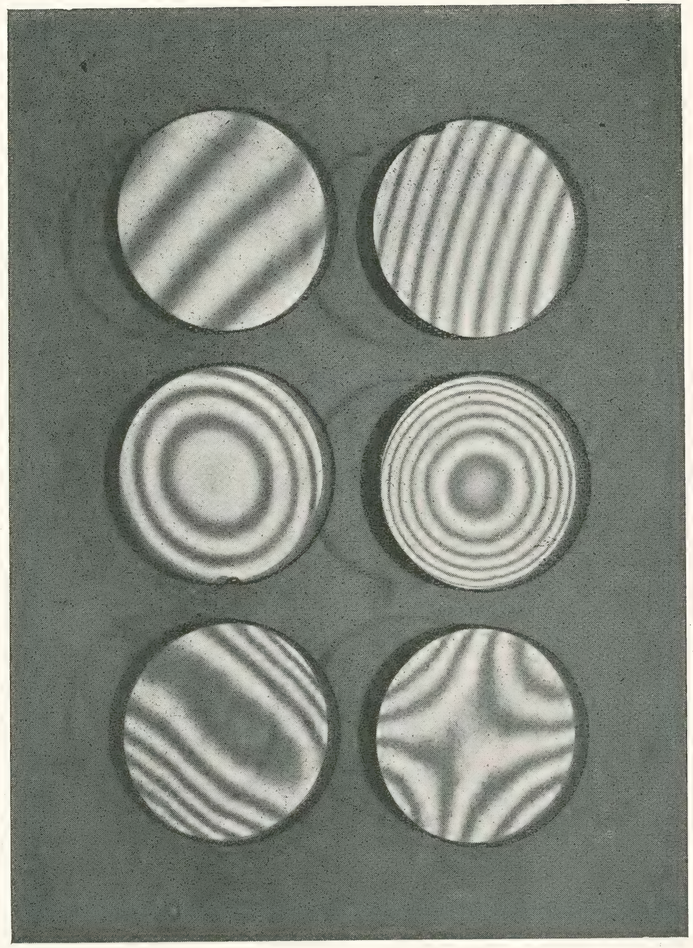


FIG. 38. The Use of the Proof Plate.

1. Nearly perfect, the proof plate slightly tilted.
2. The same, but the proof plate tilted about $2\frac{1}{2}$ times as much.
3. Astigmatic (surface slightly ellipsoidal).
4. Surface concave or convex according to the colours.
5. Strongly astigmatic.
6. Astigmatic of the saddle-shaped variety, *i.e.* concave in one direction, convex in the direction at right angles.

Fig. 38 shows a few of the appearances which may be seen between a proof plate and a surface that is under test.

Testing Angles

§181. Every optical factory should be provided with an accurate goniometer for measuring refractive indices. This should be an instrument with which refractive indices can if necessary be measured accurately to one unit in the fifth decimal place. The best one known to me is that made by Messrs. Ross Ltd. (see §210) of Clapham Common, London, which was developed under the personal direction of Sir Charles Parsons, F.R.S., the inventor of the marine steam turbine. This instrument was described in the *Proceedings of the Optical Convention at London*, 1926, p. 925. This, however, is a laboratory instrument; the responsibility of the optical glass worker is limited to the production of such angles as may be prescribed, and this is best done by comparison with a standard angle which has been accurately made and tested on the goniometer, or which has been built up from a number of smaller standards. The workshop operation can therefore usually be reduced to establishing the equality of two angles; one the standard, the other the angle which is under test.

The Angle Dekkor

§182. A convenient instrument for doing this is made by Adam Hilger Ltd. and has been used in our optical workshops for many years. It is known as the Angle Dekkor (see Fig. 39). This instrument consists of a telescope with a brightly illuminated scale at the focus at the eyepiece end, light from which is (after collimation) reflected back into the telescope by the reflecting surfaces under observation, an image of the scale being seen in the eyepiece (see Fig. 40). The position of the reflected scale relative to that of a fixed scale in the eyepiece indicates the relative angular position of the surface under test.

The instrument is employed in the following manner:

The inclination of the telescope to the polished base-plate of the instrument can be easily adjusted and it can be clamped in any desired position. If it is arranged to view the polished surface of the base of the instrument as shown in Fig. 39 the brightly illuminated reflected scale will be seen at right angles to the fixed scale and with similar dividing. Each division of the scales represents one minute of angle. By tilting the telescope these two scales can be made to cross one another as shown in Fig. 40*a*. This arrangement of scales is made so that the position of the reflected one can be controlled in two directions. If the reflecting surface (or the telescope) is slightly tilted the position of the reflected scale in the eyepiece is altered.

When *two* surfaces are being compared *two* reflected images are seen. These reflected images are cut across by the horizontal fixed scale, and the difference between the readings on the two reflected scales gives the angle between the surfaces, the fixed scale being used as an index.

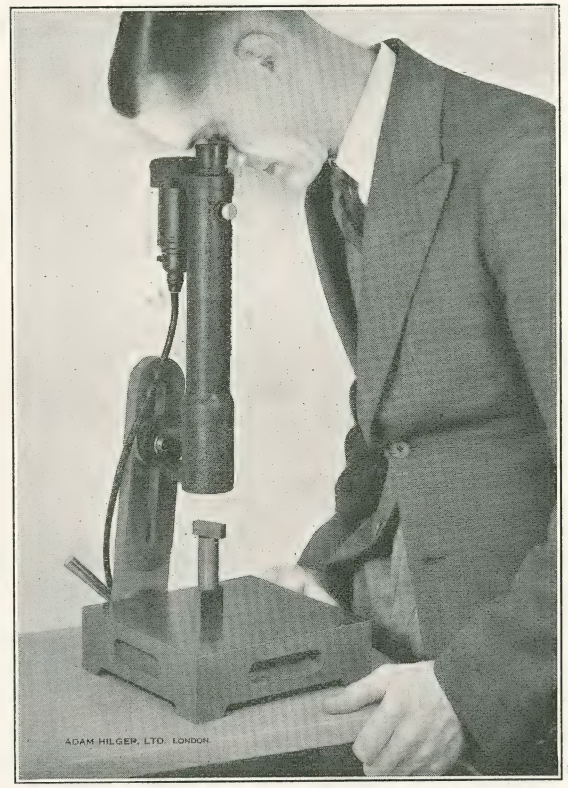


FIG. 39. Checking parallelism of ends of a tube using a Standard Angle Dekkor and Surface Plate Stand.

APPLICATION OF THE ANGLE DEKKOR.

§183. (1) **Testing for parallelism.** Parts to be tested for parallelism are mounted on the instrument as illustrated in Fig. 39 in which a test is shown on a tube 0·7 in. diameter, the ends of which are required to be parallel to one minute (a variation in length from side to side of the tube of 0·0002 in. which is not easily measured with a micrometer). The telescope is adjusted to obtain a reflected scale image from the surface plate. The tube is placed in position with an optical flat on top of it (a Johannsen gauge is shown in the illustration), when a second

scale image is produced and the difference in position between the scale images (from the surface plate and the reference plate) indicates the inclination between the ends of the tube in minutes of angle. Plane parallel plate is tested in the same way. The sensitiveness of measurement with the Angle Dekkor is about ± 6 seconds.

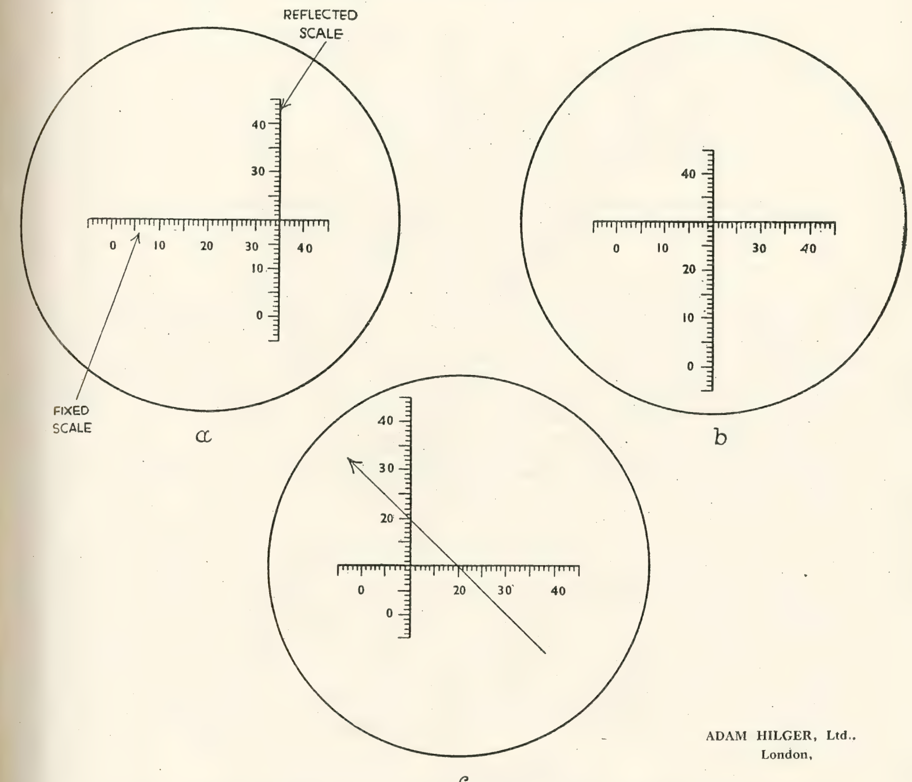


FIG. 40. Scales as seen in the Angle Dekkor. The reflected scale actually has bright lines and figures.

§184. (2) **Testing angles.** Angles are measured by using a reference gauge of known angle. The reference gauge and part under test are laid upon the surface plate and the reflections from both viewed in the telescope (see Fig. 41). Then, providing the difference in angle between the standard and the part is not too great (say less than 40′), the angle of the part can be read at once as a difference.

§185. If it is desired to avoid bringing the work into contact with any flat surface for fear of scratching, or to avoid the trouble needed to avoid dust, the reference gauge and part under test are placed one upon

another on the surface plate of the Angle Dekkor. The telescope of the Dekkor is then lowered to a horizontal position and the two pieces rotated together so that an image reflected from the lower surface appears in the field of view. The upper part is then rotated by tapping

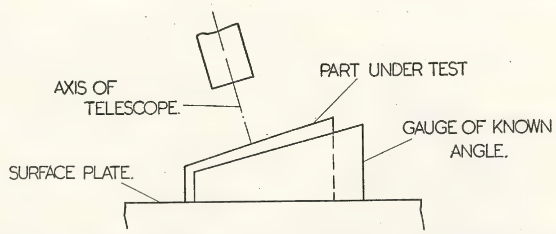
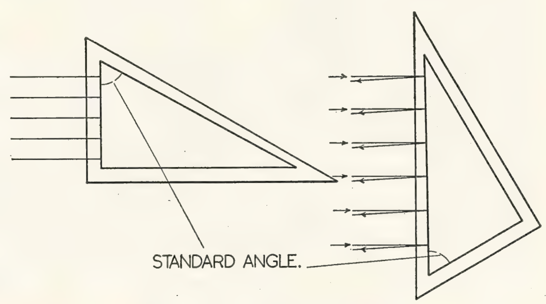


FIG. 41. Direct Comparison of Angle with a Standard Angle, using the Angle Dekkor.

it until it too gives an image in the field of view. This tapping must be continued until these two images lie along each other. When this condition has been obtained, both parts are rotated together until the other sides face the telescope. The difference in angle between the parts will then be apparent from the horizontal separation of the images. The arrangement is similar to that shown in Fig. 42.

This operation is very much simpler than it sounds, and is much used in our workshops.



a *b*

FIG. 42. Comparison of angles by means of the Interferometer.

Comparing Angles with the Hilger Interferometer

§186. For a test of equality of angles to a higher precision the Hilger Interferometer is used (Fig. 54). This is described in the next chapter, which should therefore be read at this stage. Let us suppose that two 60° angles are to be compared, one being the standard. If the bases of the two prisms are perpendicular to the polished sides a method for comparing their angles on the Interferometer is to get one face of each prism in the same vertical plane simply by standing one prism on the

other and tapping the top prism round. The parts are placed on a table of convenient height so that one face of each replaces the side mirror F in its position normal to the direction of incidence of the light from the collimating lens D. The observer should place his eye close

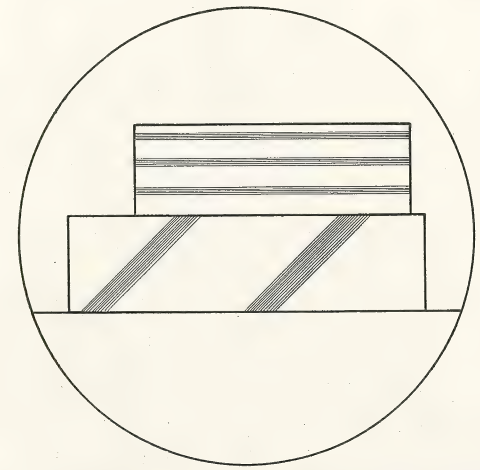


FIG. 43. Comparison of Angles by means of the Interferometer; appearance of field of view.

to the lens E. One spot of light, at least, should be seen. This spot is the image of the pinhole as seen by reflection from the back mirror G. By suitably tilting and turning the prism and the standard angle two further spots of light can be brought into view and careful adjustment will superimpose them upon one another and upon the first spot, a condition which is best observed when the eye is placed well away from the eyehole P. On bringing the eye close to P the two faces will

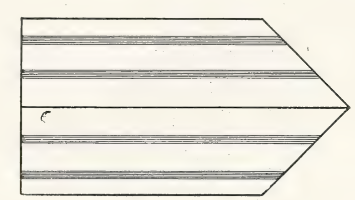


FIG. 44. Diagram of Fringes obtained in Testing a Roof Prism on the Hilger Interferometer.

be clearly seen, covered with a system of bands whose number is reduced to a minimum by further slight adjustment which can be supplemented to a very slight extent by tilting the diagonal mirror. A typical appearance as seen in the instrument is shown in Fig. 43 and

it is necessary to get both sets of fringes nearly horizontal. If no accurate levelling means are available for obtaining this condition the fine adjustment on the diagonal mirror may be utilised—provided the adjustment required is very slight.

Both prisms are now rotated so that their other faces are presented to the beam as shown in Fig. 42*b*. Needless to say this rotation must be very carefully done to avoid shifting the top prism relative to the bottom one. A slight rotation must be given to both prisms (or the diagonal plane used) in order that the fringes on the standard may be horizontal. Then, if there is any angular difference between the prisms, the fringes seen on the one prism will be tilted, the number of fringes cutting the horizontal edge of the work being a measure of this angular difference. If the interference bands are formed by the green light of a mercury vapour lamp each band represents 1/100,000 in.

§187. Testing the 90° angle of a Roof Prism on the Hilger Interferometer

The side mirror *F* of the instrument (Fig. 54) is swung round to the right angle position and the roof prism is placed on a table of suitable height to reflect the light on to the mirror. Care should be taken to see that the hypotenuse face of the roof prisms is centrally disposed with reference to the centre of the interferometer table. To set up the prism, proceed as in the above case of the comparison of angles except that there will only be two spots of light instead of three to superimpose and adjustment is made by tilting mirror *F*.

A typical appearance of a roof prism is shown in Fig. 44. Two horizontal bands appear, indicating that the angle of the roof is not quite 90°. If the angle is smaller than 90°, then by pulling the telescope rod gently in a downward direction (which increases the path length of the light reflected in mirror *G*) the fringes will move inwards towards the dividing edge.

§188. A standard set of angles as supplied regularly by Adam Hilger Ltd., consists of a block of steel whose faces produce the following angles:

30°, 60°, 90°,

together with four angle gauges:

1°, 3°, 9°, 14°.

A patent has been applied for, for this set of angle gauges.

By contacting not more than three of these together so that the angles are added or subtracted (*i.e.* placing them with apex to apex or base to apex), any angle can be set up between 0° and 90° at an interval of 1°.

They are put together in the same way as Johanssen gauges, but without the comparatively violent process of wringing that is employed by engineers in the use of these gauges.

Fig. 45. The Hilger Interferoscope.

§189. Testing the Parallelism of Plane Parallel Plates

If a number of plane parallel plates are required all of the same thickness, the purpose can be achieved with a fair degree of approximation by putting the plates down on a flat optical tool with paraffin wax, as described in the first operation of making a plaster block of prisms (§152). If the thickness of the outer glasses on opposite sides of the block is measured by a depth gauge, the accuracy of parallelism will in this way be automatically effected to within 1 or 2 minutes, and for control to this accuracy the Angle Dekkor suffices. To test parallelism to an accuracy of 1 or 2 seconds, interference methods must be applied, and the best instrument for this is the Interferoscope. The interferoscope in the form now made and used by Adam Hilger Limited is shown in Fig. 45 and in diagram in Fig. 46. Light from a mercury vapour lamp is concentrated on an aperture A by an adjustable mirror and condenser and reflected by the mirror M within the instrument on to a concave mirror, aluminised on the front, at C. This mirror collimates the rays, and reflects them up to the work holder at W. The plane parallel glass under test is put on the work holder and levelled (by means of screws S) to reflect the rays back, when the eye at E sees the surface of the plane parallel glass crossed by fringes due to the interference of the light reflected from the upper and lower surfaces. The difference of thickness of two points separated by one fringe is $0{\cdot}000{,}01/n$; n being the refractive index of the glass of which the plane parallel plate is made.

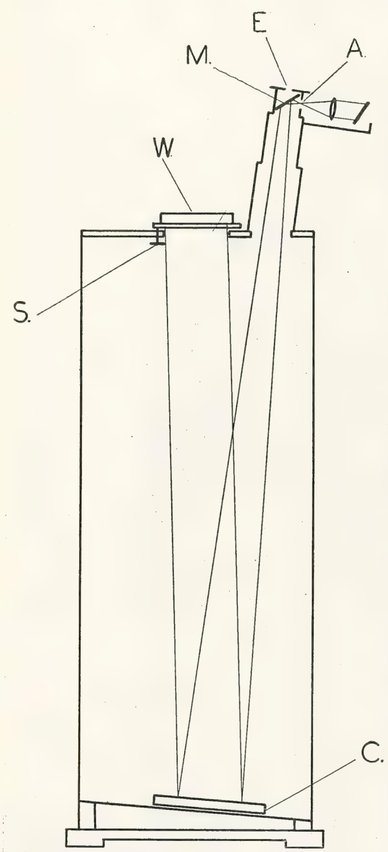


FIG. 46. Diagram of Optical System of Hilger Interferoscope.

To ascertain which is the thick part of the plate, a small copper rod, mounted in a wooden handle, is used. This rod is kept permanently heated by resting in a metal box within which a 20 watt electric lamp is kept alight. If the warm rod is held for a moment against the underside of the plate the latter is heated locally at the point of contact.

The slight expansion which takes place is sufficient to cause a slight displacement of the fringes at that spot, with the result that an appearance as shown in Fig. 47 is observed, the fringes being displaced locally towards the thinner part of the plate.

An application of the use of the Interferoscope in conjunction with the Hilger Prism Interferometer to the measurement of variations of refractive index in a plate of glass is given in §208.

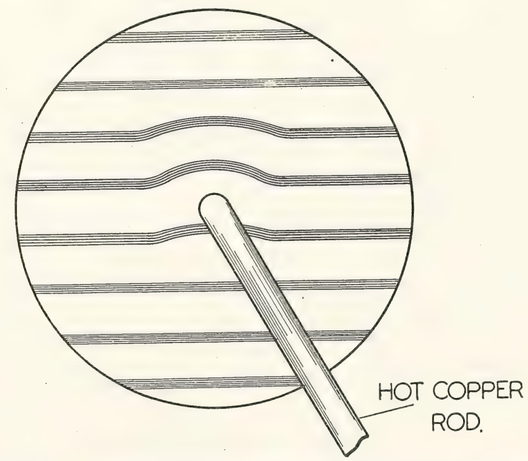


FIG. 47. Use of Hot Rod with Hilger Interferoscope.

Michelson's Test

§190. A test for parallelism was described by Michelson (1898) for the purpose of correcting large glass plates which were to be cut up for making Michelson echelons. The apparatus, shown in diagram in Fig. 48, consisted of a mercury vacuum tube, S, the light from which was concentrated by the condenser C by reflection from the half-silvered plate P on to the plate under test Q.

The light reflected from the upper and lower surfaces of the plate passed through the plate P with sufficient intensity to form circular interference rings in the focus of the telescope lens T where they were observed by an eyepiece. On passing from a thicker to a thinner part of the plate by moving the latter about in its own plane the rings are seen to open, and the replacement of one ring by another indicates that $2nt$ is increased by one wavelength of the mercury green light, where n is the refractive index and t the thickness of the plate. The relation between $2nt$ and the thickness of the plate can be seen from the table which appears below. When I was correcting echelon plates from 1898 onwards I did not find Michelson's apparatus very convenient, and in the appara-

tus which I built I made provision for marking out easily a chart which would indicate exactly where and by how much the plates should be retouched.

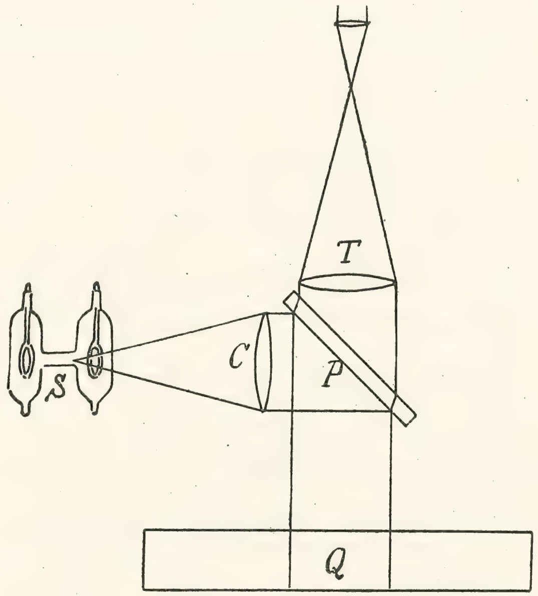


FIG. 48. Michelson Test.

In my apparatus (see Fig. 49) the plate P to be tested was placed in a circular wooden tray T, on the underside of which was a recess R in which a piece of carbon paper was placed with a piece of ordinary white paper below it, these being kept in position by drawing pins round the edge. This tray could be shifted about by hand to bring any desired point of the plate under observation.

Light from a mercury vacuum tube M was focused by the lens A on the plate. The portion of the reflected pencil which passed through the diagonal plate was received by the lens B, which produced an image of the ring system in its focus at S. The ring system was observed by the eyepiece. A graticule at S enabled one by measurement of the successive rings to calculate the differences of thickness corresponding to fractional orders of a ring.

A plunger L immediately below the point of observation could by means of a treadle, actuated by the foot, be forced upwards against the underside of the paper so as to make a black mark on the paper at the point of contact. My procedure was to find the highest or the lowest point on the plate which I was correcting, to move the tray about from that position until the ring system first seen at the lowest or highest place

was replaced by the system of the next higher or lower order, and to make a mark by lightly tapping the treadle. I then moved the tray in such a direction that the ring system neither opened nor closed, and by means of the treadle made a number of marks forming a curve which represented a contour line of the imperfections of the plate as measured in wavelengths.

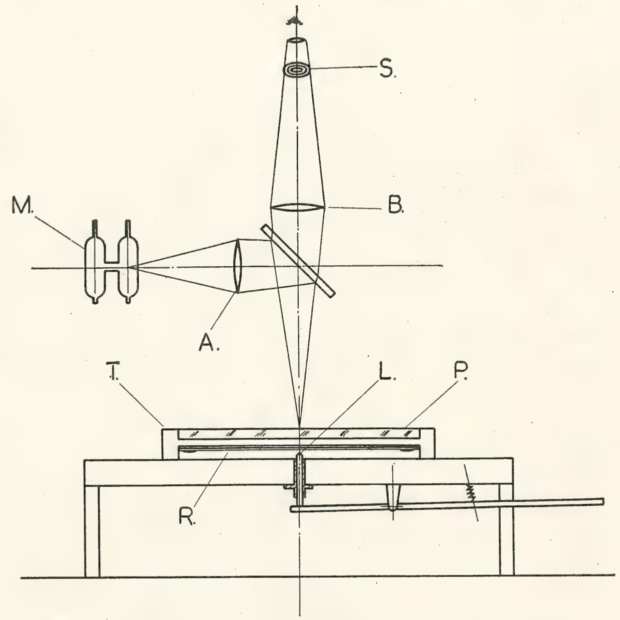


FIG. 49. Twyman's Modification of Michelson's Test.

The process being repeated for equal increments of retardation, a chart was eventually obtained such as the one shown in the Figure 49a.

I then polished the thick places with a local polisher in the manner usually adopted in retouching.

Michelson's test results in a plate in which $2nt$ is uniform, t being the thickness and n the refractive index of the glass for the radiation by which the test is made. If n varies the plate will not be correct for transmitted light, the condition for which is that $(n-1)t$ should be uniform.

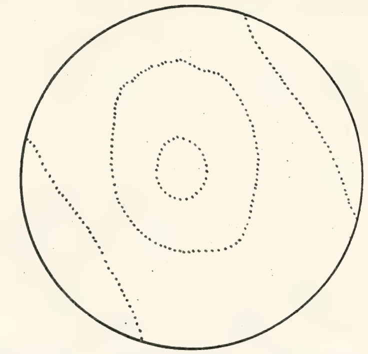


FIG. 49a. Test diagram obtained with Twyman-Michelson Apparatus.

§190.1. In making plane parallel windows and, indeed, in flat work generally, the optician is often faced with the problem of complying to a specification of the following kind.

"The window if placed in front of a telescope of 50 in. focal length must not alter the position of the image by more than one-tenth of an inch."

In such case it is convenient to have a simple relation between the appearance of the window on the interferometer and its "power".*

If the window is intended to be plane parallel, but is actually operating as a shallow lens, its appearance on the interferometer is as shown in Fig. 49*b*.

In the interferometer we are observing the interference between a plane wave front and a curved one. In Fig. 49*c* let M represent the momentary position of the plane wave front and N of the curved one.

The two waves will reinforce each other at B_1, B_2, B_3, etc., points on N separated from each other by a distance equal to λ, the wavelength of the radiation by which the observation is being made. The radius of the first ring measured from the middle point A is given by the formula

$$R_1{}^2 = 2fs_0$$

where s_0 is the difference along the axis from A to B_1 and f is the focal length of the curved wave front after double transmission through the interferometer.

Similarly, $$R_2{}^2 = 2f(s_0 + \lambda)$$

Therefore, $$R_2{}^2 - R_1{}^2 = 2f\lambda \qquad (a)$$

We have supposed that the accuracy is specified in the form that the focus of a telescope of focal length F should not be altered more than ΔF by the interposition of the window.

Since the errors are doubled on the interferometer by double transmission through the object under test then we must allow on the interferometer only an error of $\Delta F/2$. Hence f must not be less than $F^2/2\Delta F$.

Substituting for f in equation (a) we get

$$(R_2{}^2 - R_1{}^2), \text{ must not be less than } \lambda F^2/\Delta F \qquad (b)$$

To apply this expression to the specific case in question, $F = 50$ in., $\Delta F = 0{\cdot}1$ in., therefore $F^2/\Delta F = 25{,}000$ in., so that $R_2{}^2 - R_1{}^2$ must not be less than 25,000 λ.

Since $\lambda =$ (about) 1/50,000 in., $(R_2{}^2 - R_1{}^2)$ must be not less than 0·5.

If then we measure the radii of the first two rings in inches, by holding a scale near the window while looking in at the eyepiece of the interferometer, square them and subtract the squares from one another, the difference must not be less than 0·5. This accuracy is sufficient for most practical requirements.

The same reasoning may be applied to the use of the proof plane. Here it must be remembered that the curvature of the wave front

* The power of the lens is the reciprocal of the focal length. The advantage of the expression lies in the fact that if a number of thin lenses are put close together the power of the combination is equal to the sum of the powers of the separate lenses.

produced by an error of one wavelength in the surface is equal to $(n-1)\ \lambda$, or approximately $\lambda/2$. We may therefore, when using the proof plane, allow $R_2{}^2 - R_1{}^2$ to be equal to $\lambda F^2/\Delta F$.

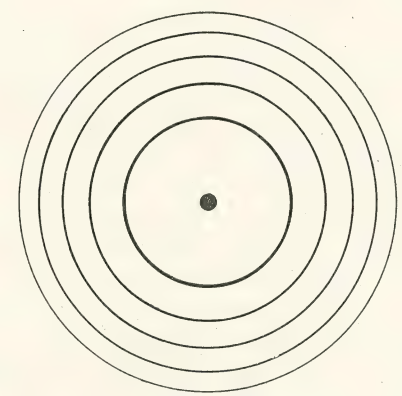


Fig. 49*b*.

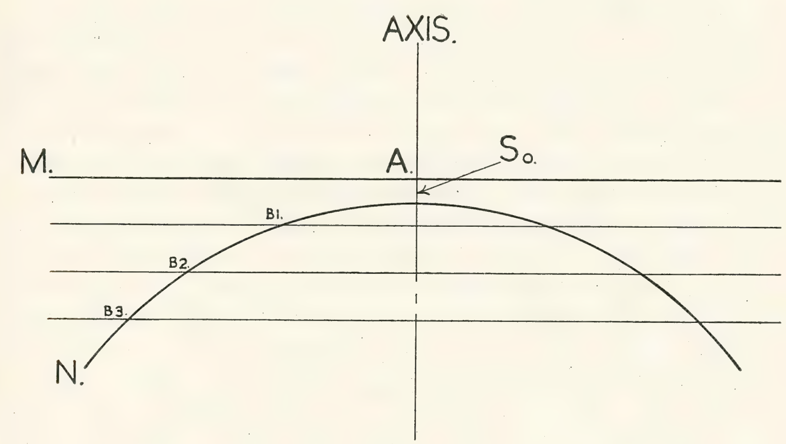


Fig. 49*c*.

TOLERANCES IN THE SPECIFICATION OF OPTICAL COMPONENTS

§191. Tolerances for Definition and for Surface

Lord Rayleigh in his article on Optics in the *Encyclopaedia Britannica*, 9th Edition, 1884, reprinted in his *Scientific Papers*, 2, 410, etc., considers what tolerance is permissible in the distortion of a wave front without impairing materially the resolving power of an optical instrument. The passage is included in a section on the resolving power of optical instruments from which the following passages are quoted :

" According to the principles of common optics, there is no limit to the resolving power of an instrument. If the aberrations of a microscope were perfectly compensated it might reveal to us worlds within a space of a millionth of an inch. In like manner a telescope might resolve double stars of any degree of closeness. . . . How is it, then, that the power of the microscope is subject to an absolute limit, and that if we wish to observe minute detail on the overlighted disc of the sun we must employ a telescope of large aperture ? . . .

" A calculation based upon the principles of the wave theory shows that, no matter how perfect an object glass may be, the image of a star is represented, not by a mathematical point, but by a disc of finite size surrounded by a system of alternately dark and bright rings. Airy (1834) found that if the angular radius of the central disc (as seen from the centre of the object glass) be Θ, $2R$ the aperture, λ the wave-length, then

$$\Theta = 1{\cdot}2197\,\frac{\lambda}{2R}$$

showing that the definition, as thus limited by the finiteness of λ, increases with the aperture.

" In estimating theoretically the resolving power of a telescope on a double star we have to consider the illumination of the field due to the superposition of the two independent images. If the angular interval between the components of the double star were equal to 2θ, the central discs would be just in contact. Under these conditions there can be no doubt that the star would appear to be fairly resolved, since the brightness of the external ring systems is too small to produce any material confusion unless indeed the components are of very unequal magnitude."

Actually, a double star can just be resolved at an angular separation of one half this. Since the disc is not of uniform brightness the phrase, " the central discs would be just in contact ", needs defining more closely. The condition is more correctly stated by Schuster (page 147), who says that it is a matter of experience that a close double star may be recognised as such when the images are at such a distance apart that the centre of the bright disc of one falls on the first dark ring of the other, *i.e.* when $\Theta = 1{\cdot}22\lambda/\Delta$, Δ being the diameter of the object glass.

The theory of image formation is simpler when the aperture is rectangular instead of circular and when the object consists of one or more bright lines parallel to one of the sides of the aperture.

§191.1. Let us then consider the case of the image of a distant fine bright vertical line, radiating with wavelength λ, produced by a perfect object glass, focal length f and of rectangular aperture, whose horizontal width is a. Then the intensity of illumination I of a point in the focal plane at a distance d from the geometric focus is given by :

$$I = I_0\,\frac{\sin^2 \pi\,(ad/f\lambda)}{\pi\,ad/f\lambda}$$

I_0 being the intensity of illumination at the geometric focus.

If we plot the values of I we get the curve shown in Figs. 50 and 51.

The points of no illumination are at distances from 0 equal to $f\lambda/a$, $2f\lambda/a$, etc.

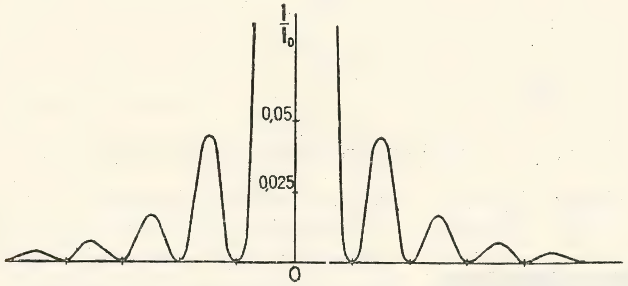


FIG. 50. Distribution of light in a slit image.

The abscissae represent the distance from the geometric focus, and the ordinates the values of I/I_0. As it is impossible to represent to scale the central maximum in Fig. 50, the central part of the curve is shown on a smaller scale in Fig. 51. (Adapted from G. Bruhat (1935) page 213.)

§191.2. The actual appearance of the diffraction pattern as photographed is shown in Fig. 52 (*top*), which was taken on a spectrograph of 150 cm. focal length with an aperture 6 mm. wide ; the line photographed is the 4358 line of mercury, the width of slit being 0·01 mm. At the bottom is seen the same line with an aperture of 50 mm. Fig. 53 shows (full line) the intensity curve produced by a lens of 100 mm. focal length of 13 mm. aperture free from spherical aberration ; the broken line that for a single lens of the same focal length and aperture of the form to give minimum spherical aberration.

In the article referred to above Lord Rayleigh's conclusion on the subject of tolerance is as follows :

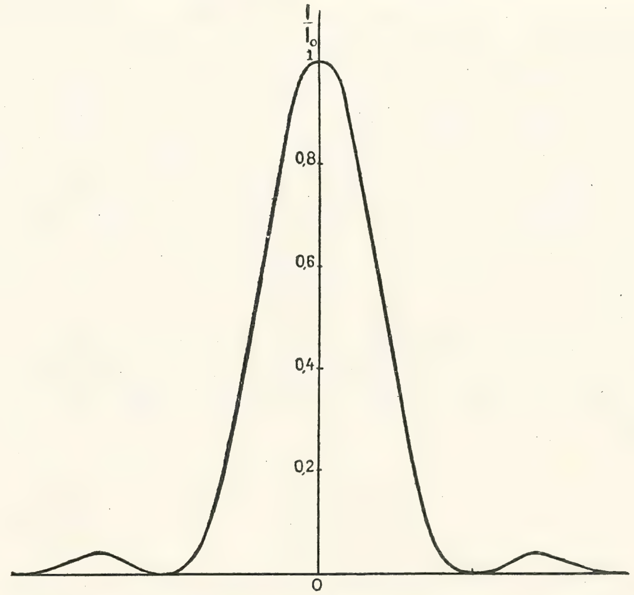


FIG. 51. Central portion of Fig. 50 on a reduced scale.

"An obvious inference from the necessary imperfection of optical images is the uselessness of attempting anything like an absolute destruction of aberration. In an instrument free from aberration the waves arrive at the focal point in the same phase. It will suffice for practical purposes if the error of phase nowhere exceeds $\frac{1}{4}\lambda$. This corresponds to an error of $\frac{1}{8}\lambda$ in a reflecting and $\frac{1}{2}\lambda$ in a (glass) refracting surface, the incidence in both cases being perpendicular."

§191.3. If the object glass is examined on a Twyman and Green interferometer an error of phase of $\frac{1}{4}\lambda$ will appear as one half band, since the error is doubled by passage of the beam twice through the object.

Let us suppose that there are two lines of different intensities, the distance between whose wavelengths is to be measured. If the error is a symmetrical one, as illustrated in Fig. 53, no error will be caused, although the measurement will be made less precise.

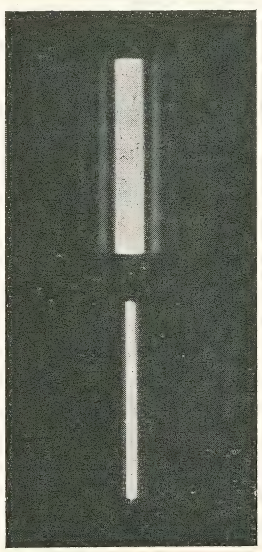


FIG. 52. Diffraction Bands.

If, however, the error is asymmetrical, the intensity curves are asymmetrical, and although the shapes are similar, the photographed images will in general not be so, for the one may be over-exposed or the other under-exposed. In such case, the measured distances between

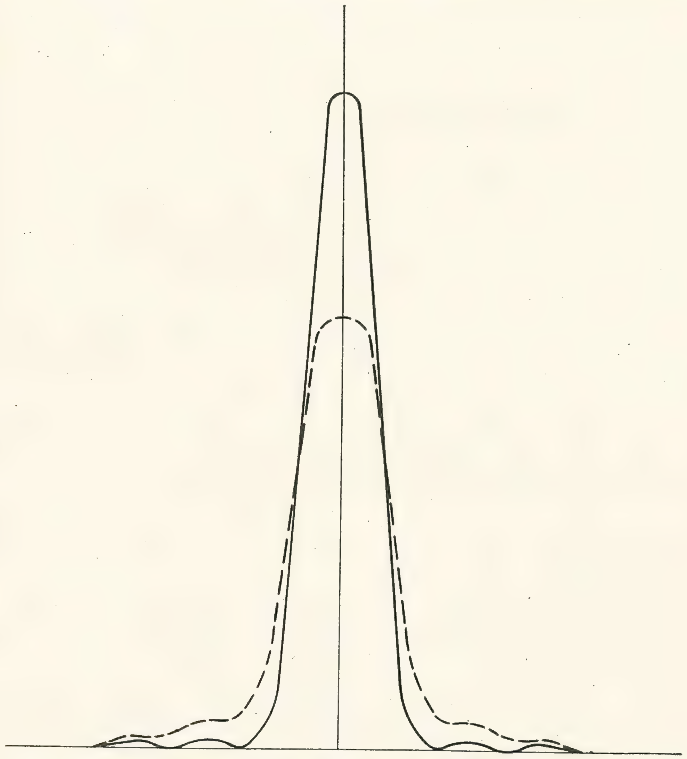


FIG. 53. Intensity curves produced by lenses with and without spherical aberration.

the apparent middle points of the photographed images may be in error by an appreciable amount. Since the accuracy with which a setting can be made on a line with a micrometer is a very small fraction (some say as little as one-fortieth part) of the resolving power, it can be understood that the presence of a phase error in the beam which will not prevent two close lines from being resolved, may cause an important error if one has to measure their distance apart, as in determining wavelengths.

Many other illustrations of this point might be given. For most purposes Lord Rayleigh's rule is a sound and safe one; for example, the phase errors produced by even the best photographic lenses (except in

rare instances for the middle of the field) are many times greater than those which can result from ordinary careful working, and an extra $\frac{1}{4}$ wavelength phase error due to faulty glass or workmanship is of no consequence. The rule cannot, however, be relied upon universally; each case must be considered separately, and the workshop drawing should stipulate an accuracy of surface appropriate to the purpose for which the optical work is to be used.

Tolerances in Angle Measurements

§191.4. Errors of angle may result either in defects of colour or of deviation, and both of these must be taken into account in fixing tolerances. For example, it has been found that a wedge of plate glass giving a deviation of $1\frac{1}{2}$ minutes does not cause enough colour to entail the rejection of any optical instrument which utilises a two-inch aperture at which point the plate glass is interposed. Let us suppose then that in an optical instrument a 2 in. aperture pentagonal prism is used and that an error of 5 minutes is permitted in the deviation of such a prism, then if

a is the error in the 45° angle

and b the error in the 90° angle

both reckoned positive if too large, then

$3a+b/2$ must not be more than 5 minutes (to keep within the permissible deviation);

$a+b/2$ must not be more than $1\frac{1}{2}$ minutes (to avoid colour),

assuming that the crown glass of which the pentagonal prism is made has approximately the same dispersion as plate glass.

§191.5. If then we wish the workshop to have the advantage of the greatest possible tolerance, a set of tables should be worked out giving the permissible range of b for each value of a between $-3{\cdot}25$ and $+3{\cdot}25$—the biggest range of a which will permit the above two equations to be satisfied. One finds on doing this that if a is $-1{\cdot}25$, b can lie anywhere between 5·5 too large and 0·5 too small; while if a is $+1{\cdot}25$, b can be from 5·5 too small to 0·5 too large. This single illustration is given to demonstrate the value of careful consideration in the matter of fixing angle tolerances.

CHAPTER IX

THE HILGER INTERFEROMETERS FOR THE TESTING AND CORRECTION OF PRISMS AND LENSES

§192. The most generally useful of the instruments built on the Twyman and Green principle, the Hilger Prism Interferometer, was designed by me and is made by Adam Hilger Ltd. for testing prisms and lenses. Other modifications of the instrument have been designed suitable for dealing with camera lenses (both for axial and oblique pencils), microscopes, and complete optical systems (for all parts of the field). The Prism and Lens Interferometer is suitable for workshop use in the operation of retouching.

Numerous methods of testing telescope or camera objectives have been devised with a view to the control of retouching.

The opinions of Schroeder, Grubb, Czapski and Alvan Clark are cited in a résumé by H. Fassbender (1913) of the then known methods of testing object glasses. This résumé should be read by all interested in the subject. It omits, however, an ingenious method of Dr. Chalmers (1912).

The more recent methods of Waetzmann (Bratke 1924) (founded on the Jamin Refractometer), Ronchi (1926) and Lenouvel (1924) (these two derived from Foucault's test), and Birch are of interest and capable —in experienced hands—of yielding useful results. Of none of them, however, can it be said—as it can of the Twyman and Green forms of interferometer—that entirely unskilled boys or girls can in a week or so be taught not only to test prisms and lenses and state precisely the nature of their defects, but to correct the optical performance by retouching the surfaces.

For this reason every optician in the Hilger works has free access to these instruments.

The apparatus here described produces a series of interference rings which may be regarded as a "contour map" of the imperfections. This contour map can for practical purposes be considered as located at any of the optical surfaces involved and, in the case of the control of retouching, the observer may, if he likes, draw this map upon the surface under treatment. He is then in a position, without further preliminaries, to remove the superfluous material from the prominences by polishing with pads of suitable size and shape, the "contour map" giving all that it is necessary for him to know both as to the location and magnitude of the sources of the imperfections.

§192.1. **General Constructional Principles**

This instrument in its simplest form resembles the well-known Michelson interferometer, the main essential optical differences being that the light is collimated and the two interfering beams of light are brought to a focus at the eye of the observer.

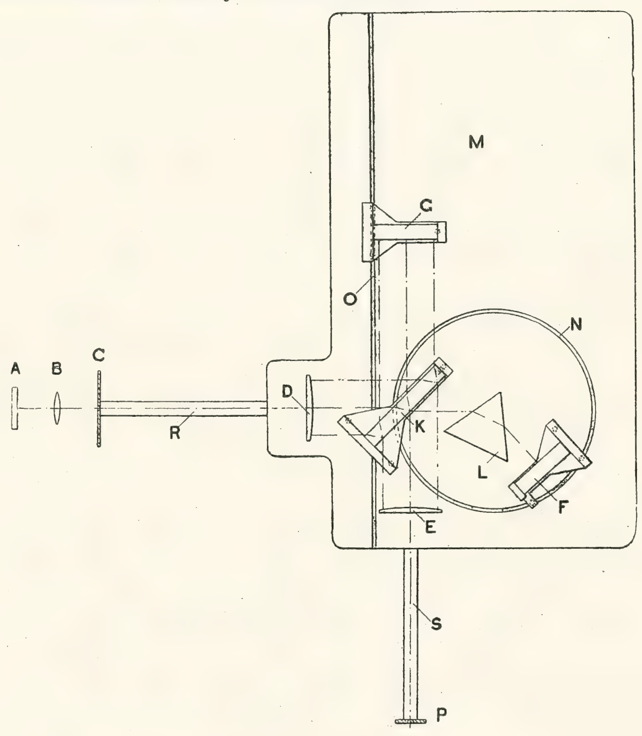


FIG. 54. Diagram of Hilger Prism Interferometer.

Optical elements or combinations suitable for examination on it may almost all be classed in two categories. Into the one category fall those combinations which are required to receive a beam of light which has a plane wave front and deliver it again after transmission with a plane wave front, and into the other fall those the object of which is to impart spherical wave fronts to beams which are incident on them with plane wave fronts. The two corresponding arrangements will be referred to as the prism interferometer and the lens interferometer respectively.

The Prism Interferometer

The prism interferometer is shown in diagram (Fig. 54) as arranged for the correction of a 60° prism, such as is used for spectroscopy.

The light used must consist of a limited number of very homogeneous radiations. Such a light may be obtained from a low pressure mercury vapour lamp with glass tube, such as the "Hewittic".

The light from the source is reflected by the adjustable mirror *A* through the condensing lens *B*, by means of which it is condensed on the aperture of the diaphragm *C*.

The diverging beam of light is collimated by a lens *D*, and falls as a parallel beam on a plane parallel plate *K*, the second surface of which is silvered (or aluminised) lightly so that a part of the light is transmitted and part reflected. The major part should be reflected. One part passes through the prism *L* in the same way as in actual use, and, being reflected by the mirror *F*, passes back through the prism to the plate *K*. The other part of the light is reflected to the mirror *G* and back again to the plate *K*. Here the separated beams recombine, and

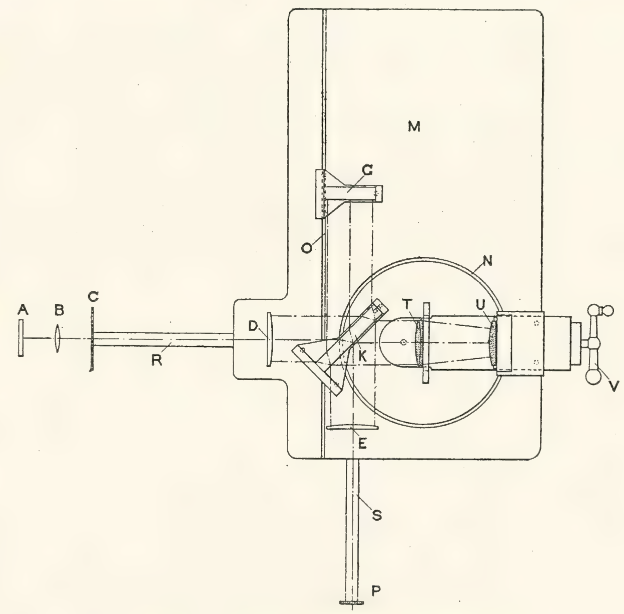


FIG. 55. Diagram of Lens Interferometer.

passing through the lens *E* each forms on the eye, placed somewhat beyond the aperture in the diaphragm *P*, an image of the hole in the diaphragm *C*.

When the mirrors are adjusted as described on p. 105, interference bands are seen which form a contour map of the glass requiring to be removed from the prism face in order to make its performance perfect.

Fig. 56 represents in diagram a typical map, where *Q* represents the

highest point of a " hill ". The procedure in such a case would be to mark out the contour lines on the surface of the prism with a paint brush and then to polish first on the region Q, subsequently extending

FIG. 56. Diagram of Interference Pattern.

the area of polishing, at first partly, then wholly, to the next contour line ; and so on. The marking out of the prism surface can be done while one is observing.

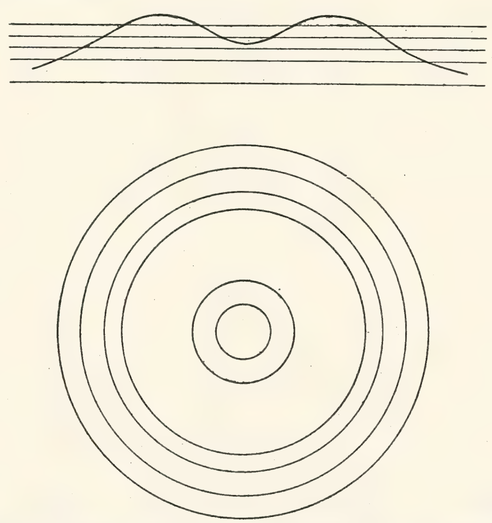


FIG. 57. Diagram of Interference Pattern for a Lens.

It should be noted that variations in the contour lines are obtained by a tilt of the plane of reference. Thus a slight adjustment of mirror F (Fig. 54) might change a contour map from that shown in Fig. 57 to that shown in Fig. 58. The form of surface is in each case the same (see

the sectional diagrams at the top of the figures), but correction can be carried out according to whichever plane of reference is the most favourable from the point of view of the operator. In order to find whether Q is a hill or a valley, the cast-iron table M can be bent with the fingers so as to tilt the mirror F in such a way as to lengthen the ray path. If the contour line at Q expands to enclose a larger area, a hill is indicated, and *vice versa*. Although the words " hill " and " valley " are convenient to use, it must not be supposed that the imperfections necessarily result from want of flatness either of one or of both surfaces of the prism. The contour map gives the total effect on the wave front produced by double passage through the prism, and shows in wave-lengths the departure from planeness of the resulting wave surface.

§192.2. Settling Down

In the final stages of polishing large prisms it is essential that before testing the prisms the temperature should be allowed to settle down. It used to be our practice to stand the prism for this purpose on three projections of non-conducting material such as ebonite to allow free access of the air all round the prism.

Although by this means an approximate equalisation of temperature throughout the prism is acquired fairly rapidly, yet until the prism has acquired the temperature of the air the equalisation is not good enough for the purpose of a critical test. The method that has been adopted, therefore, for a number of years is to stand the prism on a metal plate (which should not be too thick, so that it can rapidly accommodate itself to the temperature of the room, and should be nicely flat, so that it can rapidly convey that temperature to the prism) and to place over the prism a metallic cover nicely fitting the metal plate at the bottom and rough blacked on the outside so that it, also, rapidly acquires the temperature of the room.

In these circumstances, half an hour is sufficient for a 60° glass prism 2 in. high and $2\frac{1}{2}$ in. length of face to settle down appropriately for the most critical test. With increasing length of prism the length of time required increases rapidly ; for example, a prism 2 in. high by 3 in. length of face would require three-quarters of an hour.

It is scarcely necessary to add that for very large work a constant temperature room, in which the temperature can be held within 1/10°C., must be used.

The interferometer is very useful, also, for testing angles to a high precision. This application is described in detail on pages 104–6, §§186–7. An application of this instrument to measurements of refractive index variations in a plate of glass is given in §208.

§193. Additions for the Testing and Correction of Lenses (see Fig. 55).

In the lens interferometer all parts are left as in the prism arrange-

ment except that the mirror F is removed and replaced by the lens attachment shown in Fig. 55. T represents the lens under test, U a convex mirror in such a position that it reflects back along their own paths the rays received from T. The mirror U can be moved by a screw motion actuated by the handle V, so that its distance from T can be varied at will. It will be seen that when the adjustment of this

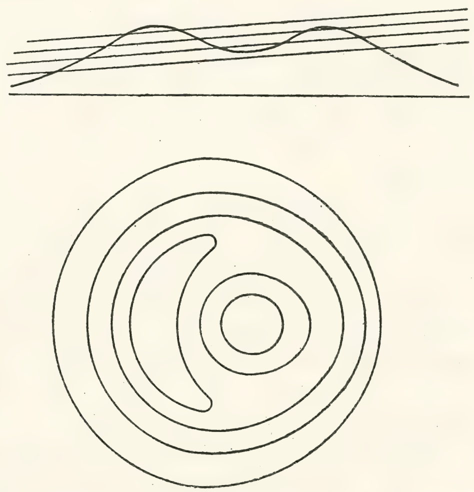


FIG. 58. Diagram of Interference Pattern of a Lens, tilted.

part of the apparatus is correct, the whole lens addition will, if the lens T be perfect, receive the beam of plane wave front and deliver it back again with a plane wave front. If it does not do so the departures from planeness of the wave front so delivered will give rise to a contour map of the corrections which have to be applied to the lens in order to make its performance, when in actual use, perfect.

§193.1. White Light Fringes. Although the forms of interferometer described above suffice for the ordinary purposes of prism and lens manufacture, there are some occasions when valuable information may be obtained from the use of a compensated system with which the interference bands are obtainable with white light. (See for example §208·1).

Compensation is attained by replacing the prism in Fig. 54 by a second diagonally-placed plate exactly similar to K but unsilvered. Under these circumstances both the beams traverse the same thickness of glass. In order to get the white light bands it is necessary to adjust the position of the mirror C with great nicety, and for this purpose a slow motion is provided by means of a screw.

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CHAPTER X

MICROSCOPE LENSES

§194. The manufacture and testing of microscope lenses involves peculiar difficulties, arising from the smallness of the lenses and their short radii of curvature. Microscope lenses properly so called are not at present to be numbered among the manufactures of Adam Hilger Ltd., but the following notes may be of interest. The front lens of a high-power microscope is always either hemispherical or more than hemispherical in shape, and often less than $\frac{1}{10}$ in. diameter. When it is borne in mind that the radius of curvature of these small lenses requires to be made to the calculated radius to within $\frac{1}{10000}$ in. and that the lenses must in addition be truly spherical in shape, we realise the necessity of special means to ensure these conditions. Although pitch is sometimes used as a polisher it is more customary to use such a mixture as shellac and putty powder, otherwise the methods of grinding and polishing already described are applicable with such modifications as are implied by the small size and other characteristics (their deep curves, and the fact that in some cases they are hemispheres or more than hemispheres) distinctive of the deeper lenses used for microscope objectives.

§195. These lenses of hemispherical or hyperhemispherical shape are worked to proof plates which have been made up by being tested against complete spheres of glass of the appropriate diameter. The advantage of this method lies in the fact that the diameter of such a sphere can be directly measured with a micrometer gauge to $\frac{1}{10000}$ of an inch, which will be accurate enough for front lens work. An alternative method is to turn up a disc of glass to the required diameter, to round and polish the edge of this disc of glass and then to test the proof plate on the rim. When the proof plate is of the correct radius an interference figure consisting of a black line bordered by coloured fringes can be seen extending along the line of contact. These two are the most common methods in use in workshops and can be relied upon for the order of accuracy already stated. It is clear that the glass disc method can be used for quite big radii of curvature without giving a great deal of trouble, whereas for the small radii of curvature the complete sphere of glass is probably but little more difficult to make than a corresponding disc of the same radius.

The methods described will enable lenses to be made of the appropriate radius of curvature and they may be tested against proof plates, but to apply the test successfully special methods are devised, including

special optical instruments, whereby the surface can be inspected very nearly as a whole and the light used for the inspection purposes is made to traverse normally the thin film of air between the lens and proof plate over nearly the complete extent of the film. Precise details of the methods used will vary from maker to maker, but the testing is usually based on the simple principle of the inspection of the Newton ring pattern with the appropriate instrumental modifications which are necessary to render this inspection foolproof.

There is no doubt that nowadays the hyperhemispherical front lens of a microscope objective is a portion of a very perfectly made sphere, in spite of the fact that it is one of the most difficult surfaces to make and that any small error shows up to a marked degree.

§196. The method of centring does not differ in principle from that adopted in the case of larger lenses. The method in general use seems still to be to observe the reflected images as seen when the lens is mounted on a true revolving chuck. The successful setting and edging of the lens is, however, an operation of considerable skill. The mechanical accuracy of the mount also wants special care, particularly the process of mounting and cementing the front lens, the spherical surface of which bears against a shoulder, the lens being centred and cemented in position with shellac.

In optical instruments the centring tolerance for a surface will vary from surface to surface according to the conditions of refraction through that surface and the centring tolerance for a homogeneous immersion front lens is reasonably large, so that when once it has been perfectly made the centring does not offer quite the same difficulties as its manufacture. On the other hand, the portion of the front lens which is available for mounting is exceedingly small, varying from $\frac{1}{5}$ mm. to $\frac{1}{10}$ mm., and the satisfactory solution of the problem of holding it securely is one that calls for co-operation on the part of the user, ensuring that no large stresses are brought to bear on the front lens or cell.

§197. A customary test by users of microscope objectives is to examine a familiar object such as a *Podura* scale or one of certain diatoms such as *Amphipleura Pellucida*. The utility of these objects usually depends on the presence of regular markings of more or less constant separation which thus constitute a test of the resolving power of objectives of stated N.A. A better test of resolving power is to be found in the Grayson rulings, consisting of ten fine diamond lines ruled on realgar surfaces. These are made at the University of Melbourne and can be obtained (though not so plentifully as one might desire) with rulings down to $\frac{1}{120000}$ of an inch. The manufacturer, however, requires to assist him to achieve perfection in his lenses an indication not only that the lens is imperfect, but of the nature of the imperfections. The reflection of light from a very small mercury globule gives him a small

point of light which will serve a like purpose to that of the star in the observation of the rings of the diffraction disc in the testing of telescope lenses. In place of the mercury globule, the light transmitted through a selected accidental perforation in a piece of silvered glass can be used with advantage. The observation of the ring system inside and outside focus with either of these kinds of object affords in either case an indication of the accuracy of the aberration correction or of the manufacture of the lens. But here again a special difficulty applies in the case of the microscope, for the aberrations, which in the case of a telescope are of a simple character (involving in the calculation terms of the second order only), in the case of the microscope are of much more complex character. This complexity is reflected in the appearance of the rings; not only their brightness but also their disposition being strongly affected by the aberrations of the various zones, so that judgment of the correction required is very difficult. Information of a more direct character is obtained from observing the appearance within and without focus on the exposure one by one of narrow zones of the objective, but here again considerable experience is needed before a right judgment can be come to. It should here be noted that, even in the repetition manufacture of an approved type of objective, the maker requires to make a final correction of aberration, which is effected by slightly altering the position of one of the lenses, and an improved test for this part of the manufacture is much to be desired.

The means that appears likely to afford the most direct information on this subject is provided by the microscope objective interferometer, the application of which to this problem of the aberrations of microscope lenses seems likely to afford valuable information.

CHAPTER XI

TESTING OPTICAL GLASS

§198. It is well that the optician should know how to test optical glass for its various faults, although the optical glass made in this country is now so good that it is not necessary in the ordinary course of manufacture to test it in its raw state except in the case of large pieces for individual working.

The broken pieces straight from the pot are examined at the glass works, those being rejected in which veins, dead metal or excessive bubbles can be seen.

The glass is broken with a hammer into pieces of about the size required; any large pieces which would form specially large prisms or blocks are often set aside and reserved for such purposes. The pieces are then moulded into lens shapes, plates or prisms and annealed.

The plates or blocks are usually supplied polished on both sides so as to facilitate a thorough examination. The defects which can then be detected are as follows:

§199. Veins

Veins are threads or streaks of glass within the mass having a refractive index so different from the bulk of the glass as to be distinguishable to the eye. They consist chiefly of glass which has dissolved the sides of the pot and has then been carried by convection or by stirring into the body of the glass.

A vein may be surrounded by quite good glass but there is often what one may call a hank of veins presenting—as is natural, having regard to their cause—the appearance of water in which sugar has been dissolved.

A further source of veins, though of far less importance, is the layer of glass at the top of the pot which acquires a different refractive index owing to the evaporation of the more volatile constituents (Twyman and Dalladay, 1921a).

§200. Bad veins are easily detected by what our opticians call "flareing". The glass (which needs to be polished on two opposite surfaces) is held between the observer's eye and a distant bright light. Using a magnifier of say 4 inches focal length at about the same distance from his eye so that the source of light is focused on the latter, the observer then holds the piece of glass at such a distance as to view the surfaces and interior through the magnifier. Even faint veins then become plainly visible as dark lines or bright lines accordingly as the light

is focused exactly on the eye or a little to one side of it. This simple procedure alone almost suffices to reveal all injurious veins but if the piece of work is an important one, more delicate tests are applied. We ourselves examine it by the *schlieren* method (*see* §172) and by the Hilger interferometer (§192 *et seq.*). Another method due to M. Albert Arnulf, practical instructor at the Institut d'Optique, is described by Dévé (1936, pages 27–31). (The following is a free translation of that description.)

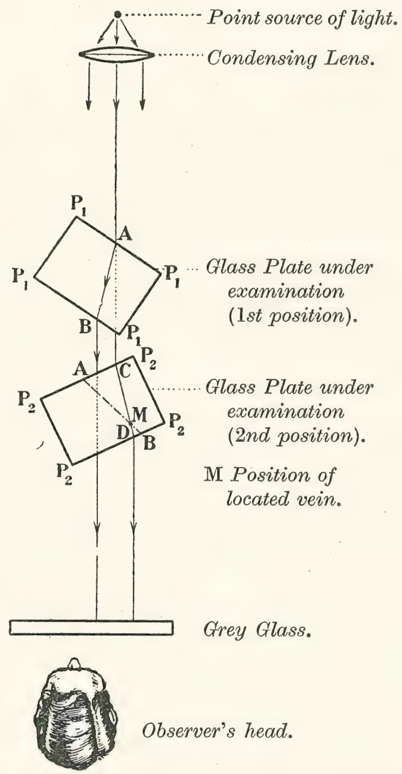


FIG. 59. Location of Faults in a Plate of Glass (from Dévé).

§201. A small brilliant source of light such as a Pointolite Lamp is placed several yards from the plate of glass or optical piece which is to be examined. Between the latter and the observer is a grey glass which receives the shadow of the piece of glass. In the shadow appear black and sharply-defined shadows even of the smallest defects (Fig. 59).

The phenomenon is the same as that observed in the evening when a thin stream of water runs from a tap in a room lit by a lamp. The

water is almost invisible but its shadow on the wall is as black as that of a pencil. The explanation is that the light which falls on the stream of water mostly passes through it and, since the remainder is reflected in all directions, only a very small amount reaches the eye. On the other hand, the light which enters the thread of water is refracted in all directions, and the part which arrives in a direct line at the wall is very small in amount so that the shadow is very intense. In the glass, veins act like a stream of water.

The method even reveals imperfect polish on a plate of glass.

§202. Double Refraction

If we apply force to a piece of glass, as for example by trying to bend it, we cause stresses and strains within it. The stress at a point consists of the forces acting on the small portion of glass around that point, and the strain is the amount of distortion of that portion caused by the stress.

Such a condition separates the molecules by a greater distance in one direction than in the directions at right-angles to it and this causes the electro-magnetic waves of which luminous radiation consists to separate into two waves travelling through the glass at two different speeds, resulting in double refraction similar to that caused by Iceland spar. The degree of double refraction varies with the strain from point to point of the glass and may be detected by a simple form of polariscope designed for the purpose, to which I gave the name of the "Strain Viewer". The form of strain viewer mostly used in this country embodies an improvement known as a tint plate or half-wave plate, first described by Brewster in 1830 and applied to the strain viewer by Mr. F. E. Lamplough, of Messrs. Chance Bros. & Co., about 1914. In this form the instrument shows regions of stress in vivid colour contrast. Well-annealed specimens have no effect on the colour of the purplish pink background, while regions of stress become a light blue or yellow red according to the direction of stress.

§203. A convenient form of strain viewer is shown in Fig. 60.

The apparatus is so arranged that any article can be held by the hand in a beam of polarised light at a convenient distance from the eye, when the presence of strain is revealed by distinct changes of hue in the portions of the object which are in tension or compression. The field of view, including all parts of the glass which are not strained, remains a magenta tint, and the condition of strain is readily judged from the hue of the strained parts. Optical glass should not be held in the bare hand while under test for strain, but left for a time resting on a wooden or other non-conducting support for its temperature to become uniform.

§204. We have just been considering the effect produced by applying an outside force to a piece of glass, but internal stress can exist. This is caused by certain parts cooling first and thus becoming rigid

while other parts which cool more slowly have their contraction resisted by the already cooled portions. The effect is that, broadly speaking, those parts which cool first are in compression, those which cool later are in tension. These internal stresses are revealed by the strain viewer just as those are which are caused by the application of external force.

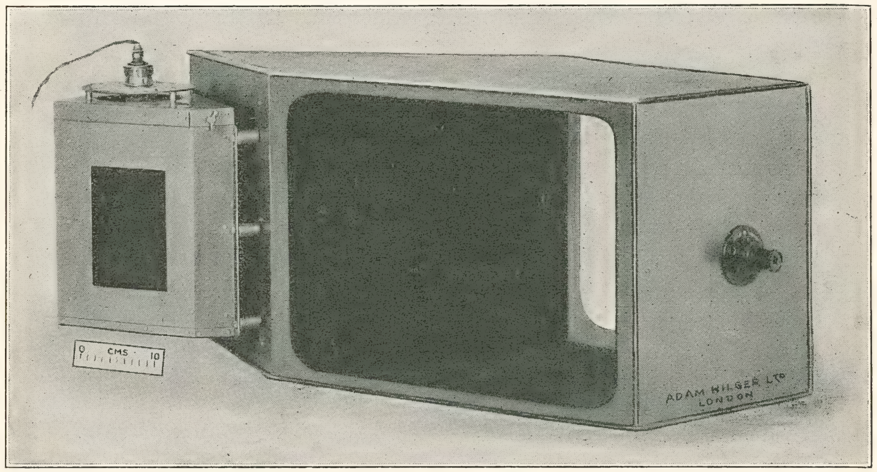


FIG. 60. Hilger Strain Viewer.

Glass which has not been sufficiently well-annealed after the chilling which takes place in moulding shows double refraction, but the effect can be quite marked on the strain viewer without in itself causing optical parts made from the glass to be defective. For example, double refraction amounting to one-tenth of a wavelength gives very brilliant colour effects on the strain viewer but is without practical detriment to the definition. It is, however, evidence that the heat treatment has been such as to leave in the glass heterogeneity of the kind referred to below, and on that account no glass showing this amount of strain should be used.

§205. Prior to the last war it was customary to spend several weeks in the annealing of optical glass, and it was obvious to me therefore in 1914 that annealing would constitute one among the many difficulties in the way of producing in this country the greatly augmented supplies that were needed. I therefore offered to carry out for Messrs. Chance experiments to determine a rapid way of finding the best temperatures at which to anneal the numerous kinds of glass made by them, some of them not previously made in the country. Messrs. Chance were sufficiently interested to pay for the necessary apparatus and I proceeded with the work on lines I had been considering for some time previously.

Working with specimens provided by Messrs. Chance, my assistant, Mr. A. J. Dalladay, and I were able to establish the now generally accepted law of variation of viscosity of glass with temperature in the range of temperatures in which annealing can take place. From this I was able to deduce the best temperatures to which to raise the various glasses and the cooling schedules which should be followed in order to get sufficiently complete removal of strain in a comparatively short time. My methods and apparatus were adopted by Messrs. Chance with the result that in a few months prisms which had previously taken fourteen days to anneal were being brought to the same state of annealing in $4\frac{1}{2}$ days.

At the present date this time has been still further reduced, and I see no reason why optical glass should not be dealt with in the same way as glass bottles, travelling through a lehr with carefully controlled temperatures, the whole process being completed in six or seven hours. The limiting factors appear to be, first, the length of time the glass must be held at the annealing temperature in order that the temperature may become uniform throughout and for the glass to become normalised to that temperature, and secondly, the differences of temperature that must necessarily exist in an object which is cooling. I believe, however, that, adopting the exponential cooling schedules originated by me (see Appendix C), the speed I have indicated could be reached if necessary. Later on I applied my methods to the annealing of glassware with very satisfactory results and an account of part of the work was published (Twyman, 1917).

On one point, however, the procedure I recommended gave no guidance—the length of time necessary to soak the glass at the annealing temperature in order to remove the effect of chilling introduced in moulding.

§206. Heterogeneity of Refractive Index

Veins are, of course, a form of heterogeneity, but under this heading I refer to changes of refractive index much more gradual in character and arising from a quite different cause. I have never seen heterogeneity in glass which gave the impression of being due to failure to mix the sand and the powders from which the glass is made ; the glass in its broken lumps ready for moulding is usually very homogeneous, with the exception of any veins that may be present.

During the last war when very large numbers of moulded lenses were used, I had been greatly impressed with the fact that certain glasses when moulded were very defective even after annealing. The effect was specially marked with dense barium crown. Dr. Simeon and I therefore investigated the matter (Twyman and Simeon, 1923). It had long been known that fine annealed glass has a refractive index higher than

the same glass not fine annealed. In the experiments referred to we studied the effect of chilling, that is to say, rapid cooling from a high temperature as opposed to controlled cooling from the annealing temperature. We found that a dense barium crown allowed to cool in air from a temperature at which it began to flow on a sheet of iron upon which it was heated had a refractive index of 1·5955 whereas the same glass when carefully cooled from the annealing temperature (591° C.) had a refractive index of 1·5986.

The same kind of effect though in a less degree was caused by chilling other kinds of glass.

The lowering of refractive index caused by chilling was, we found, removable by soaking at the annealing temperature for two hours, whereas more than 90 hours at a temperature of 520° C. failed to do so.

§207. It is obvious therefore that two purposes are served by annealing optical glass; as indeed they are in the annealing of metals. One is to remove internal strains, the other is to normalise the glass so that it should be of uniform refractive index throughout the mass. To the optician the first of these problems used to be considered of prime importance. It is now known, however, that this view was mistaken. To quote from a recent paper by Hampton (1942) (read at the Inaugural Science meeting of the Optical Group of the Physical Society on 6th March, 1942), " sufficiently slow cooling reduces these birefringence effects to a negligible amount and the old test of an annealing schedule was that it should reduce the double refraction to something of the order of 0·01 wavelengths per cm. (=5 millimicrons per cm.). It was found, however, on occasion that glass which appeared satisfactory from the point of view of double refraction and which was known to be free from striations still did not give a satisfactory optical image and it was certainly possible to find two pieces of glass which, while appearing equally satisfactory in polarised light, gave substantially different pictures when examined on an interferometer."

How, one may ask, can this be reconciled with the conclusion of Simeon and myself that two hours at the annealing temperature sufficed to normalise the glass to the refractive index appropriate to that temperature? The explanation and the remedy were provided by work carried out at the British Scientific Instrument Research Association in collaboration with the laboratories of Messrs. Chance. To quote once more from Dr. Hampton's paper: " if a piece of glass is uniform in temperature while being held prior to the annealing operation, the only index changes introduced into it will be the plus or minus variations due to the temperature gradient during cooling and these will probably be small; probably not more than a few units in the fifth decimal place . . . Without the most elaborate precautions it is very difficult to get any sort of annealing kiln where the temperature differences are so small as not to give a risk of departures across a slab of optical glass of the order of 10° C. Much experimental work therefore has been directed towards the provision of annealing equipment where the temperature differences are negligibly small, and kilns have been designed and are in use where the temperature difference over a length of two feet or more does not exceed 3° or 4° C. These kilns are capable of being cooled at a much higher rate than the old type while still yielding glass which is of the highest standard when viewed on the interferometer although the strain viewer pattern may not be appreciably different from that given by less uniform kilns. Experience has shown that the glass which is satisfactory on the interferometer, due to the absolute uniformity of index, is capable of being used for the very highest type of optical instrument and it is becoming generally accepted in the optical industry that the interferometer is the instrument to be used and not the strain viewer. It is now a routine operation for samples from all kilns of optical glass to be examined on the interferometer and for the strain viewer to be used to a considerably less extent.

" There was for many years an objection which was based on painful experience that the highest quality prisms could only be obtained by sawing from large blocks and not by moulding. Since moulding is much more economical in the use of optical glass than cutting up large pieces, recent developments in annealing which have proved beyond doubt that moulded prisms can give results equal in quality to those produced by any other method have been of the utmost importance in amplifying the supply under the present emergency conditions."

The interferometer referred to by the author is the Hilger (Twyman and Green) interferometer (see §192 *et seq.*).

For observation on the interferometer two opposite surfaces are polished and to avoid the necessity of polishing them very accurately flat, plates of plane parallel glass are placed over these surfaces with a liquid in between the block under test and the plates of glass, of refractive index equal to that of the latter.

The block of glass is then observed on the interferometer, see §192. Unless the surfaces are polished very accurately parallel, such a test will not, of course, reveal a linear change of refractive index in a direction at right-angles to the light path, but for practical purposes it may be assumed that a block which shows no " error " is satisfactory to use even for work of the highest quality.

It will sometimes be found that the system of interference fringes seen on the interferometer is indistinct in places. This is because of double refraction which is due to faulty annealing. This indicates that the degree of double refraction is sufficient to impair the optical performance.

§208. Measuring Small Differences of Refractive Index

There are occasions when it is desirable to determine the variations of refractive index throughout a block or plate of glass. In this case there is no escape from the necessity of making the surfaces fairly flat and fairly parallel, but extreme accuracy is not necessary. To give an example, it was suspected that a 4 in. diameter disc 0·4 in. thick was heterogeneous in refractive index. The disc was polished fairly parallel, and tested on the interferoscope and the N.26 interferometer (see §189 and §192). In Fig. 60*a* the dotted lines show the dark bands as seen by reflection, the full lines those seen by transmission. The band in each system indicating the least equivalent thickness is marked 0. Then if n is the mean refractive index of the glass in a direction perpendicular to the surfaces at any selected place, t the thickness at that

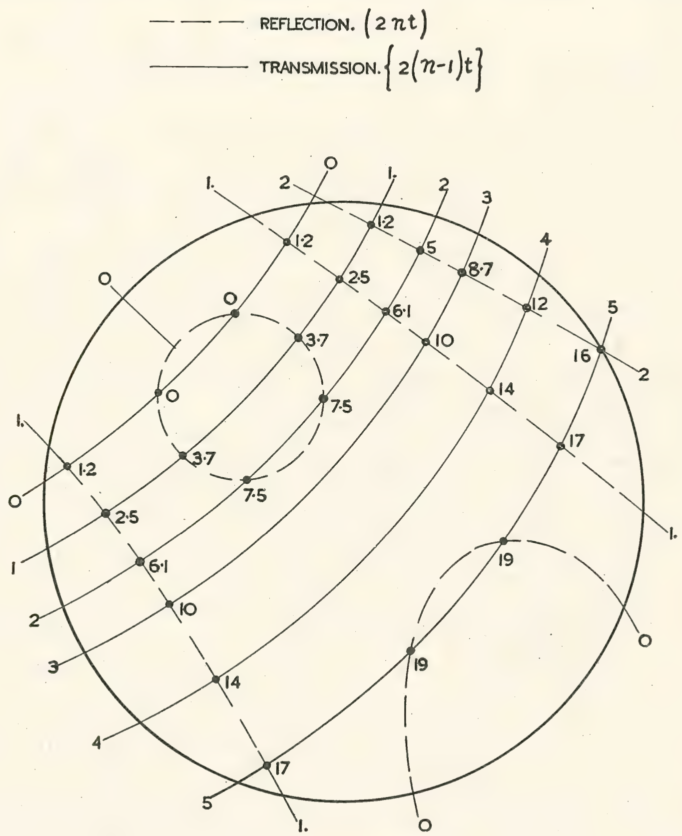


Fig. 60*a*.

place, m_r and m_t the orders of the bands of the reflected and transmitted reflections respectively,

$$\Delta n = \{n(m_t - m_r) + m_r\}\lambda/2t \quad \text{(Twyman and Perry 1922).}$$

For the points of intersection of the two systems of bands the evaluation of Δn is very simple. Full details of the determinations are given in the table below. The refractive indices in units of the fifth decimal place are marked in the figure at the points of intersections.

m_r	m_t	$m_t - m_r$	A $=1{\cdot}5(m_t - m_r)$	B $=m_r + \text{A}$	$n = \text{B} \times \lambda/2t$ $= \text{B} \times 0{\cdot}000025$	t $\times 10^{-5}$ (inches)
0	0	0	0	0	0	0
	1	1	1·5	1·5	0·000037	−1·0
	2	2	3	3	0·000075	−2·0
	5	5	7·5	7·5	0·00019	−5·0
1	0	−1	−1·5	−0·5	0·000012	+1·0
	1	0	0	1	0·000025	0·0
	2	1	1·5	2·5	0·000061	−1·0
	3	2	3	4	0·00010	−2·0
	4	3	4·5	5·5	0·00014	−3·0
	5	4	6	7	0·00017	−4·0
2	1	−1	−1·5	+0·5	0·000012	+1·0
	2	0	0	2	0·000050	0
	3	1	1·5	3·5	0·000087	−1·0
	4	2	3·0	5·0	0·00012	−2·0
	5	3	4·5	6·5	0·00016	−3·0

The variations in thickness at the same points can be found with equal ease from the expression: $\Delta t = (\lambda/2)\ (m_r - m_t)$.

The method is easily accurate to about 5 units in the sixth place for the refractive index, and to about one-millionth of an inch for the thickness. The accuracy for refractive index could, if necessary, be pushed higher.

It will be noticed that there is no sudden jump in refractive index. Nothing, that is, that would indicate that the variations are due to veins or to faulty mixing. The natural inference is that the differences must be due to the variations of temperature during the annealing process referred to in §207.

The glass was therefore annealed again in an experimental furnace with controlled temperature, using the annealing temperatures determined by the apparatus described in §237 *et seq*. The plate was then re-worked and it was found that there were no variations of refractive index exceeding two in the fifth place of decimals. That is, the disc was

nine times as good as before re-annealing. The re-annealing was kindly carried out by the British Scientific Instrument Research Association.

§208.1. Measuring Small Differences of Refractive Index in Separate Pieces of Glass

The above method can be extended to deal with separate pieces of glass which differ only slightly in refractive index and thickness.

The two pieces to be compared are worked nearly to the same thickness but slightly wedge-shaped so as to show, say, 10 to 20 bands on the interferometer by transmitted light. They are then mounted side by side, each on a separate levelling table, in one of the beams of the interferometer. They are levelled until the reflected spots coincide as seen at the eyepiece of the interferometer.

The fully reflecting mirrors of the interferometer are covered and one then sees at the eyepiece the bands produced by interference of light reflected from the front and back surfaces of the two pieces.

The colour sequence of the bands obtained with mercury light are not such as to enable one to identify in the two plates bands of the same order, but one can do so if a cadmium lamp is used (an Osira Cadmium Laboratory lamp made by the General Electric Co., England, is suitable).

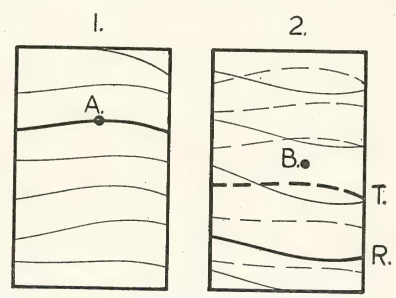


FIG. 60*b*.

Let n be the refractive index for a point A in one piece (Fig. 60*b*) and $n+\Delta n$ that for a point B in the second piece; t and $t+\Delta t$ the thicknesses for the same two points. The point A is so chosen that an identifiable interference band runs through it. That band having been identified in the second piece at R, the number of bands from it to point B is recorded. Call this m_r, counting m_r as positive if the band at B is of a higher order than that at A.

The fully reflecting mirrors of the interferometer are then uncovered so that the interference bands of transmission are seen.

The instrument must have a compensating system (§193.1) and a piece of glass similar to the pieces under examination in the comparison beam. Under these circumstances one can obtain a black band, easily

identifiable, and one adjusts the instrument so that this runs through A. As before, having identified this black band in the second piece at T, one records the number of bands from it to point B. Call this m_t, counting m_t as positive if the band at B is of a higher order than that at A.

One can then find Δn and Δt from the expressions given above.

Refractive Index

§209. Where large numbers of highly corrected lenses, such as camera lenses, are to be made, it is highly desirable that the refractive indices should be known to one unit in the fifth place, and for such purpose a very high precision goniometer is required, such as that mentioned below. For routine factory testing of glass as it comes in, a Pulfrich refractometer is sufficient.

§210. For the measurement of refractive indices to high accuracy the usual forms of refractometer are not suitable, and the routine use of the usual form of high accuracy spectrometer for this purpose has the disadvantage of being too time-consuming. For such purposes the method and the form of apparatus advocated by Abbe, depending upon the principles of auto-collimation, have distinct advantages. A large auto-collimating goniometer for accurate routine refractive index measurement based upon this principle and of modern design was made in 1926 (Hasselkus, 1926), and this type of instrument has since then been adopted for use where routine refractive index measurements of high accuracy require to be made. This instrument (see Fig. 61) is of massive construction, the fixed auto-collimating telescope having an apochromatic object glass with focal length 400 mm., aperture 44 mm. diameter. The divided circle is 18 inches diameter, divided every 5 minutes, the circle-reading, indicating the position of the prism table, being observed by two microscopes reading directly to half seconds. Fine setting is by the aid of an accurate link motion replacing the usual tangent screw. The test prism, of angle about 30° and reflecting at its back face, is mounted upon an adjustable prism table, and owing to the use of auto-collimation the adjustment for minimum deviation is permanently obtained for the wavelength upon which the telescope is directed for observation at any time.

Measurement of the prism angle is made as part of the routine test upon any prism, a whole set of measurements for any one glass requiring not much more time than that required for a similar series of measurements using the ordinary form of refractometer. The accuracy obtainable is considerably greater, however, being well within one in the fifth decimal place for absolute refractive index, while for dispersion measurements made differentially it is a fraction of this. The prisms for refractive index measurement should, of course, be of homogeneous

material and the surfaces should be flat to an accuracy corresponding to the absolute refractive index accuracy required. For ordinary purposes this, generally speaking, does not need to exceed a flatness accuracy of one Newton's fringe and is well within the capabilities of an optician of average attainments.

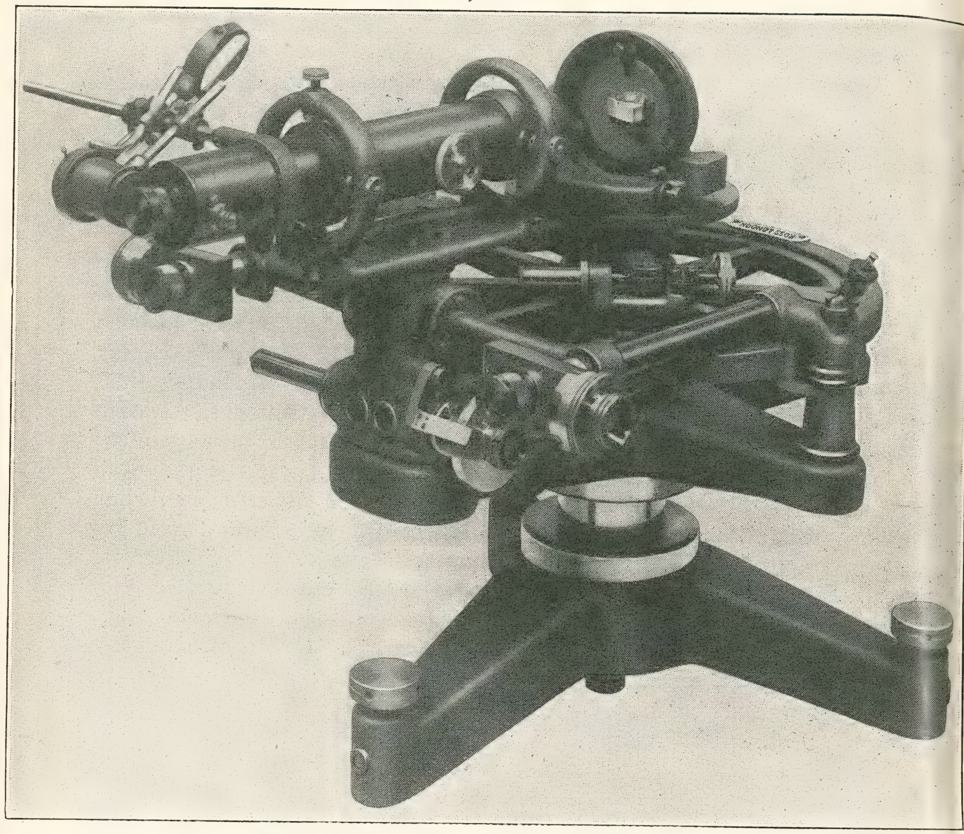


Fig. 61. Ross Autocollimating Goniometer.

§211. The Pulfrich refractometer (Fig. 63) is designed for the measurement of the refractive indices of both solids and liquids with an accuracy of about 0·0001, and the dispersion to about 0·00002.

A water-jacket forms an integral part of the instrument for control of the temperature.

A glass prism of high refractive index has two plane polished faces which are perpendicular to one another, and is so placed that one of these is vertical and the other horizontal. The substance whose refrac-

tive index is required is placed upon the horizontal surface, and a beam of monochromatic light is directed almost horizontally through the substance so that it meets the prism face at grazing incidence. The emergent beam is bounded sharply by that ray which actually grazes

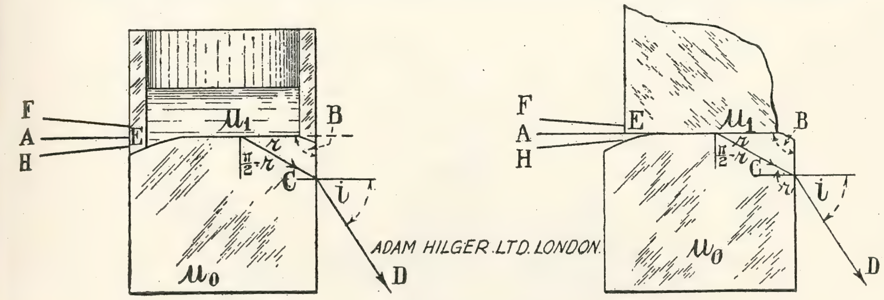


Fig. 62.

the prism surface, and the sharp boundary is observed with a telescope attached to a divided circle. On this circle, whose axis of rotation is horizontal, the angle of emergence of the beam from the vertical prism face can be read to one minute with the aid of a vernier. For making measurements of dispersion a clamp and micrometer screw are provided, the smallest division on the drum head of the micrometer screw corresponding to 6 seconds of arc. A condensing lens and supporting rod for a hydrogen vacuum tube form part of the apparatus.

A small reflecting prism is also provided so that another source of light, *e.g.* a sodium flame, is easily interchangeable with the vacuum tube.

§212. The path of light is that shown in Fig. 64 where F, A and H represent the directions of incidence of the convergent pencil of light entering the glass specimen on top of the Pulfrich refractometer block. A represents a ray parallel to the plane of separation between block and specimen and coincident with it, and is therefore the last possible ray to enter the block. It will correspond with the sharp edge of the light portion of the field of view, upon which a setting is made. Means are provided for determining the normal to the face of the block, and the angle measured is between this normal and the direction of the emergent light, i. This can be translated into the refractive index of the specimen for the light used either by means of tables supplied with the instrument or from the expression :

$$n_1 = \sqrt{n_0^2 - \sin^2 i}.$$

where n_0 = refractive index of Pulfrich block ;

n_1 = refractive index of specimen ;

i = angle between refracted ray and normal to the exit face of the block.

§213. The specimens used do not require very accurate preparation, so long as the surface which is to go into contact with the top of the block is well polished, plane, and there is an unbroken sharp edge between it and the face by which the light enters. The surface of contact should be flat to an accuracy of one Newton's band. The entrance face must be approximately normal to the surface of contact and, so long as

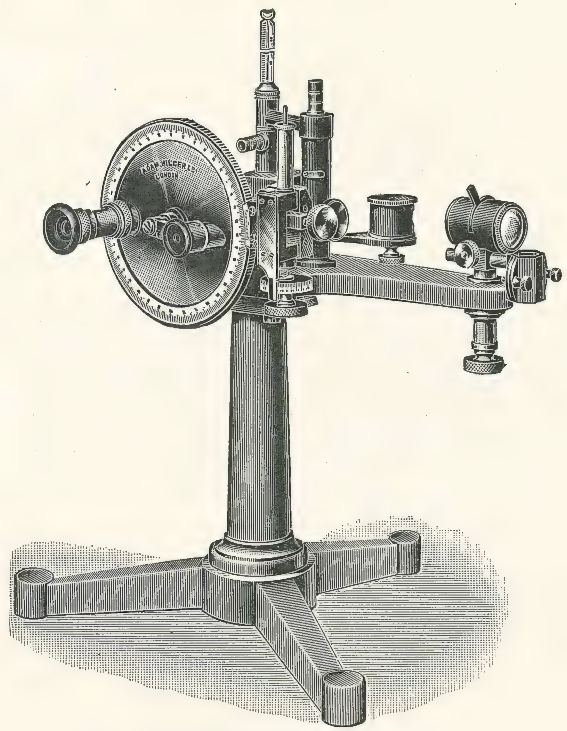


FIG. 63. The Pulfrich Refractometer.

it is reasonably translucent and meets the surface in a sharp edge, it need only be " buffed " or roughly polished. It can be quite small in height.

The dimensions of the test specimen are unimportant so long as the surface of contact is large enough to cover the whole of the circular, plane surface on top of the Pulfrich block, and the entrance face is more than a few millimetres in height. Specimens of excessive size are undesirable. Suitable dimensions are about $20 \times 25 \times 10$ mm.

§214. When putting the specimen in contact with the block by means of the usual fluid (monobromonaphthalene), care should be taken that only a minimum quantity is used and that none of it is allowed on the

edge separating the entrance face from the surface of contact, or a " false edge " may appear in the field of view. Both block and specimen should be carefully cleaned and dusted and a single drop of the contacting fluid should be put on the specimen, which should then be held face downwards while the top of the block is finally dusted before placing the two in contact. Observation of the fringes formed in monochromatic light will verify the thinness and parallelism of the film of liquid.

§215. It is desirable to have a member of the staff whose duty it is to examine all materials as they come in. If the controller of materials is provided with simple slitting and polishing equipment, there is no reason why he cannot himself cut and polish a prism and test it on the Pulfrich refractometer for refractive index and dispersion within an hour of receiving the specimens. It can usually now be assumed of optical glass made in this country that all from the same melting is of the same refractive index with sufficient accuracy for practical purposes.

APPENDIX A

LIGHT SOURCES USED IN OPTICAL MANUFACTURE AND TESTING

FOR GENERAL LIGHTING AND THE USE OF TEST PLATES

§216. The most useful illuminant in the optical workshop and in the testing room is the long tube, low pressure, direct current mercury vapour lamp such as is supplied by the Hewittic Electric Co. This lamp gives a mercury spectrum of well-defined lines with little or no background, and test-plate fringes seen by its light are strong and distinct.

Where conditions permit, as in the testing room, it facilitates test-plate tests if a diffusing screen of fair size is fitted up at an angle of about 60° over a board covered with dark velvet cloth or green baize. The board can be large enough to accommodate several test plates and the sloping diffuser above it can be conveniently made from tracing cloth stretched on a light wooden framework.

The same illuminant is also very suitable for the use of the Hilger Prism and Lens Interferometers. When monochromatic light is required the mercury green line (5461A) can be sufficiently isolated by filters.

FOR LOCAL MONOCHROMATIC ILLUMINATION AND REFRACTOMETRY

§217. Gas Discharge Lamps (G.E.C.-Hilger)

These, particularly those filled with neon, can be run on ordinary electric light current at 200 volts, D.C. or more, and give a line spectrum which can be used with the interferometer when no mercury lamp is available. Their brilliance is not high and the luminous area is restricted. The form known as the Osglim lamp is a possible substitute for the mercury lamp for test-plate observation since its luminous area is reasonably large but its intensity is low and the spectrum contains more lines. They can be used on A.C. with shortened life.

§218. Osira Metallic Vapour Discharge Lamps

These give relatively simple spectra of high intensity and are suitable for refractometry, though their pressure is rather high for interferometry. Forms are available giving the spectra of sodium, mercury, cadmium, mercury and cadmium, and zinc. They have a high intensity and are steady. Zinc lamps run on A.C. only. All others are supplied in separate types for A.C. or D.C.

§219. Gas Sodium Flame

For emergency working and for occasional refractometry a sodium flame can be used. A simple way of obtaining such a flame of moderate

intensity is to place a fair-sized bead of sodium borax on the grid of a Meker burner or one of the upright Bray burners. This needs little or no attention and burns quietly without crepitation or fumes. A chip of rock-salt may be used similarly, but is liable to " spit " until it has fused.

§220. Vacuum Tubes

For refractometry, since custom has established the hydrogen lines for refractive index (although the lithium and mercury lines are more easily obtained and better spaced), a hydrogen vacuum tube should be used. This is preferably of the Guild type, with a large attached bulb. The best means of excitation is a small transformer, such as is used for neon signs, giving about 15 milliamperes at 2000 volts. (Such transformers can be obtained from Claude General Neon Lights Ltd., Transformer Type A.2.)

APPENDIX B

THE PREPARATION OF REFLECTING SURFACES AND ANTI-REFLECTION FILMS

§221. Metallic reflecting surfaces from which light is to be reflected directly (*i.e.* front surface reflectors) may be prepared by chemical or physical methods. The deposits may be opaque or translucent.

§222. Chemical Silvering

A method of chemical silvering which is extensively employed in the Hilger workshops is a modification of Brashear's method and is described in the following (extracted by permission from *Discussion on the Making of Reflecting Surfaces*, The Physical Society of London and the Optical Society, 1920, pages 18–20, C. R. Davidson).

The method employed is essentially the Brashear process, with slight modifications, a description of which was published by Mr. Brashear in the *English Mechanic* in 1893. Its merit is that it gives a hard enduring film which will stand a considerable amount of polishing.

The formula as used is as follows :

A. 10 per cent. silver nitrate solution.
B. 25 per cent. ammonia (0·880).
C. 10 per cent. caustic potash solution.
D. Reducing solution :

Distilled water	2,000 c.c.
Sugar	180 grms.
Nitric acid	8 c.c.
Alcohol	350 c.c.

A, B and C may be made as required. The reducing solution should be made up several months before it is required, as when freshly made it is not very active. It may be improved by boiling, the alcohol being added after it has cooled.

The silvering bath is made up in the following proportions :

A. (silver nitrate)	20 c.c.
B. (ammonia)	10 c.c. (more or less)
C. (caustic potash)	10 c.c.
D. (sugar)	5 c.c.
Distilled water	100 c.c.
	145

To prepare the bath :

Of A (silver) take, say, 100 c.c. and to this add B (ammonia) gradually. The solution at once turns brown. Continue adding ammonia, in quite small quantities, until the solution clears or nearly clears. Now of C (potash) add 50 c.c. The mixture will again thicken, turning dark brown. Again slowly add ammonia as before, keeping the solution agitated till it again clears. The solution will now be a pale brown colour but transparent. This part of the operation is a critical one, as it is important to avoid an excess of ammonia. In fact, it is absolutely necessary to have a slight excess of silver in the solution, and this is secured by now adding silver drop by drop until the solution will take up no more, and a little brown matter is left in suspension.

To 500 c.c. of distilled water add 25 c.c. of D (sugar).

When the silver-potash solution is added to this the bath is completed, but this must not be done until the mirror is ready for silvering.

A mirror may be silvered either face upward or down as circumstances decide. Small work is preferably silvered face down, but large mirrors are more easily handled face up. The dish for the bath should be of glass or porcelain, but large baths may be of wood or sheet metal thickly coated with paraffin wax, and for economy should be of nearly the same size as the mirror to be silvered. In the case of very large mirrors it is most economical and convenient to make the mirror itself form the bottom of the bath.

Cleaning.—The cleaning is one of the most important operations. Unless the work is absolutely clean failure must result. All dust is removed and the old silver cleaned off with strong nitric acid, using a swab of cotton wool. Considerable pressure should be applied and the swabbing should be very thorough. Wash with water and with nitric acid swab again. Rinse off the nitric acid using plenty of ordinary water followed by distilled water. Finally, leave the mirror standing completely covered with distilled water. It is now ready for silvering.

In the cleaning operation it has been recommended that the nitric acid be followed with a swabbing with caustic potash. Our experience is against this, the nitric acid being more easily removed than the potash.

In addition to the varying activity of the sugar solution the temperature has a very large influence on the result. Working under somewhat unfavourable conditions, it is not practicable to exercise much control over this factor.

A temperature of 65°–70° is recommended as giving the best results, but with the 30 in. mirror we have generally to be content with a temperature not much above 55°, and the proportion of reducing solution has to be increased to suit that condition. It may be taken, however, that if the temperature is too high, reduction will be too rapid, and the resulting film soft, whilst if too low action is very slow and the film too thin.

The amount of sugar solution required must be found by experiment at the time of silvering by making three small test baths, using :

(1) normal reducer,
(2) 25 per cent. more,
(3) 25 per cent. less,

and judging by the result.

We left the mirror covered with water. This is now thrown off and the water and sugar poured on; then the prepared silver potash solution is added. At the same time a conical swing is given to the suspended mirror so that a continuous wave passes round the bath. This must not cease until the exhausted solution is thrown off. The drawback to the Brashear process is the formation of sediment which must be prevented from settling on the mirror surface by keeping the solution constantly in motion. This may be further assisted in the following manner :

Immediately the prepared silver is added to the water and sugar it begins to darken and in two or three minutes there will be a visible coating of silver. As soon as there is an appreciable deposit it will be found tough enough to stand light swabbing with cotton wool. Using rubber gloves, the operator takes a handful of cotton wool and draws it lightly over the surface, exerting no pressure beyond the weight of the swab itself. This will disturb the heavy sediment which, as the bath gets thicker, the motion of the solution is unable to prevent falling. As the cotton becomes dirty it is thrown away and a fresh handful taken.

It is a difficult point to decide when to throw off the solution. If too soon, the film will be bright but thin. If too late, the deposit will be thicker but clouded and will require much polishing. The former alternative is preferable. One must be guided by the preliminary experiments and experience.

When the silvering is judged completed, throw off the spent solution as quickly as possible and wash thoroughly with distilled water. If lightly swabbed during the washing much of the cloudy bloom on the surface will be removed, and when dry it will be found to require very little polishing. Stand the mirror in a tilted position to dry and in an hour it will be ready for polishing.

The polishers are made of best chamois leather stretched and tied over a ball of cotton wool. Two are necessary. First with a plain rubber go over the entire surface with light circular strokes, dusting constantly. Then rub a little rouge into the other and repeat. If the film is a good one it will take a high polish with very little rubbing and with very little scratching. The rubber must be scraped from time to time or any particles that may be polished off will cause scratching.

§223. Chemical Half-Silvering

For such objects as the diagonal planes of Michelson or Hilger interferometers whose silvered surfaces must be semi-transparent a convenient chemical method is available.

Solutions

Prepare the following stock solutions :

A

10 per cent. Silver Nitrate.

B

40 per cent. Formalin.

C

Granulated Sugar	- -	400 grms.
Alcohol	- - - -	200 c.c.
Nitric Acid	- - -	10 c.c.

Make up with distilled water to 2000 c.c. and allow to stand two weeks before using.

D

Chromic Acid	- - -	250 grms.
Sulphuric Acid	- - -	1500 c.c.

Procedure

The glass plate is placed in a glass dish, and cleaned first by strong nitric acid swabbed over the surface by small wads of cotton wool twisted round the end of a stick or glass rod, and then by allowing the glass to stand in some of *D* solution for $\frac{1}{2}$ minute. Pour off solution, rinse the plate thoroughly by a stream of running water, lifting the plates with a glass rod, to allow acid to escape from beneath the glass

plate. Take 20 c.c. of *A* solution, add ammonia until the precipitate is *just* redissolved, add silver nitrate solution (any strength) until the liquid is a faint straw colour. Make up to 100 c.c. with distilled water.

Reducing Solution

$$\left.\begin{array}{l}5 \text{ c.c. of } B\\ 5 \text{ c.c. of } C\end{array}\right\}\text{mixed.}$$

The mirror can be suspended with the face either upwards or downwards in the ammoniacal solution of silver. Then add the reducing solution. Keep the solution in constant motion until it becomes reddish in colour. Pour off the solution and put in a second quantity of the ammoniacal solution of silver *without* any reducing solution. Allow the mirror to remain until the required density of deposit is obtained—this will take a few minutes only. The plates can then be rinsed with distilled water and dried. No polishing is required, the deposit being bright and uniform.

For the interferometer it is better to have the deposit of silver rather dense.

For the fully silvered mirrors any of the usual silvering processes may be used.

METAL-ON-GLASS MIRRORS

(Contributed by Dr. K. M. Greenland, of the British Scientific Instrument Research Association.)

§224. " Physical " Processes

There are two physical methods by which metal reflecting films are deposited on glass. In both methods the metal is volatilised and condenses on the polished glass surface.

The volatilisation may be induced by bombarding the metal with gaseous ions in a moderate vacuum ; in this process, called " sputtering ", the metal source remains comparatively cool.

The other method is to heat the metal in a very high vacuum to a temperature sufficient to make it evaporate freely.

§225. Sputtering

The general method and apparatus have been fully described in Strong's *Modern Physical Laboratory Practice* (Blackie, 1940), which also contains data on the rate of sputtering of metals in various gases. Special precautions for the sputtering of good silver films are described by Gwynne-Jones and Foster (1936).

The gas discharge is generated in a glass vessel large enough to allow plenty of space between the mirror and the walls of the vessel. The gas pressure is reduced to within the range 1 mm.–10^{-2} mm. of mercury by means of a mechanical vacuum pump. The chosen gas is allowed to

flow slowly through the gas chamber or the system is flushed with the gas several times before sputtering is begun.

A dissipation of about 50 watts at a voltage of from 500 v. to 20,000 v., preferably D.C., is required to produce the gas discharge.

The metal to be sputtered is made the cathode, and the anode is a ring or plate of aluminium or of the same metal as the cathode (Gwynne-Jones and Foster, 1936). The cathode should be of about the same size and shape as the surface to be coated and parallel to it.

In the range of pressures used for sputtering, the discharge dark space surrounding the cathode extends to a distance of not more than a few centimetres from the cathode and the mirror surface is placed so that it is tangential to the boundary of the dark space.

The rate of deposition is slow, so that even the easily sputtered metals such as silver, gold and platinum may take an hour to form an opaque film, but this has the advantage of allowing accurate control of the density when semi-transparent films are required.

§226. High-Vacuum Evaporation

The metal is heated electrically in a space in which the pressure is of the order of 10^{-5} mm. of mercury. It then evaporates freely, the vaporised molecules travelling in straight lines, and condenses on any relatively cool surface exposed to the heated source at distances up to two feet. For small mirrors the usual working distance is from 3 in. for the less volatile metals to 8 in. or 10 in. for aluminium and chromium, but these distances are not at all critical.

The design of the vacuum equipment and operation of the process is described in detail by Strong (*loc. cit.*). Additional information on high-vacuum technique is given by Kaye (*High Vacua*, Longmans, 1927).

This technique for metallising glass on a large scale has been made possible by the development of high-speed diffusion pumps, since to make successful mirrors by this method without an elaborate procedure for degassing the vacuum apparatus it is necessary to remove large quantities of gas during the actual evaporation. Where time of operation is an important factor a very liberal estimate of the required pumping speed is strongly recommended. A pumping speed of 120 litres per second at 10^{-5} mm. of mercury is not excessive for vessels from one to two feet in diameter.

The highest pressure at which the heated metal will vaporise and condense as a bright adherent film is about 10^{-4} mm. of mercury. In practice the pumps and vacuum vessel are designed to enable the lowest possible pressure to be reached in a reasonable time, and pressures in the region of 10^{-5} mm. of mercury are now reached and maintained in metal evaporation chambers two or three feet in diameter.

The diffusion pump depends for its operation on a moderately low pressure at the outlet and is therefore " backed " by a rotary mechanical pump. The pumping speed of rotary pumps falls off rapidly at the lower backing pressures so that a small diffusion pump is often interposed between the main diffusion pump and the rotary pump. The pumping speeds of the backing pumps are chosen so that each maintains an adequate vacuum at the outlet of the preceding pump when the main diffusion pump is working at full output.

The type of heater for the metal depends upon the form in which the metal is available, but some form of electric resistance heater is always used. When the metal can be obtained as wire, short lengths are wound or hung on a suitable resistance wire, to which they will cling when molten. A table of heater wires suitable for a number of metals is given by Caldwell (1941). Tungsten wire (0·5 mm. diameter) is used for several metals and the wattage necessary to provide a given temperature can be calculated from the wire tables available (*G.E.* 1927). Evaporation temperatures for the metals are given by Strong (*loc. cit.*, p. 169) but the heater temperature must sometimes be made much higher on account of bad thermal contact with the evaporating metal. Brittle metals, such as chromium, obtainable in chips, may be evaporated from closely wound spirals or " baskets " or, if powdered, from troughs of molybdenum, tantalum, or tungsten. A very convenient method for precious metals which avoids waste is to deposit the estimated quantity on a spiral heater by electro-plating. A heater to be plated must be brought to white heat in a vacuum before plating, to clean it.

Both the metal and its heater will have been impregnated with oil and gas during manufacture, and it is usual but not essential to fuse the metal on to the heater before the glass is put into the chamber.

§227. The adherence of the evaporated metal film is greatly improved by subjecting the glass surface to ionic bombardment in a gas discharge. This is generated in the evaporation chamber before the main diffusion pump is started. A discharge of 100 mA. for 30 minutes is recommended for a chamber 15 in. in diameter.

§228. Choice of Mirror Metal and Method

Silver has the highest reflectivity (about 95 per cent.) in the visible spectrum when freshly deposited, but it tarnishes quickly and is soft. For normal indoor applications, aluminium is suitable. Its reflectivity can be as high as 90 per cent. and it is hard enough to be cleaned frequently, especially if deposited on a thin undercoat of chromium.

For mirrors exposed to corrosive atmospheres, platinum and rhodium are suitable. Although they have lower reflectivities than aluminium,

they do not deteriorate at all. Rhodium mirrors are very durable under all conditions.

Aluminium and platinum mirrors also have good reflecting power in the ultra-violet. The reflectivity of silver falls off sharply in the near ultra-violet and there is a band of very low reflectivity in the range used, for instance, in ultra-violet therapy. The high reflectivity of aluminium is, however, maintained in this region. Reflectivities of several metals in the ultra-violet are given in a paper by Sabine (1939).

Silver and platinum mirrors can be made by the sputtering method, which has the advantage of comparative simplicity.

The more elaborate high-vacuum process is necessary for metals such as aluminium and chromium which do not sputter easily. It is also more convenient for large mirrors, especially those of the precious metals.

§229. Defects in Sputtered and Evaporated Mirrors

Poor reflectivity is due to presence of dirt, grease or oil vapour or, in the high vacuum process, too high a pressure.

Pin-holes are caused by dust particles or pits filled with rouge in the glass surface. They also develop quickly in films having poor adhesion.

Adhesion depends on the cleanliness of the glass and, in the high-vacuum process, the gas discharge and the vacuum.

" Frosting " occurs with mirrors of platinum and rhodium if they are not made to adhere well. It is due to absorption of water vapour which causes the film of metal to swell, forming blisters which ultimately break.

The bluish-white bloom on aluminium mirrors is due to too high a rate of deposition.

ANTI-REFLECTION FILMS ON GLASS

§230. The intensity of light reflected by a polished glass surface is between 4 per cent. and 7 per cent. of the incident light, depending on the refractive index of the glass.

This surface reflection is greatly reduced, and the transmission increased, by forming on the surface a transparent film of such a thickness that interference takes place between the light rays reflected at the air-film and film-glass surfaces.

(A full explanation of the theoretical principles of anti-reflection films is contained in a paper by K. Blodgett, 1939.)

The conditions for no reflection of monochromatic light are that the refractive index of the film shall be the square root of that of the glass and that its optical thickness shall be one quarter of the wavelength of the light.

The reduction of reflection at wavelengths on either side of the chosen wavelength is also considerable. The result is that with a film giving

minimum reflection for yellow-green light the red and blue reflectivities are also considerably reduced, and with incident white light a faint purple reflection is seen.

To detect the correct thickness of film it is therefore sufficient to observe either its colour in white light or the brightness of the reflection of a monochromatic light.

§231. The value of the refractive index of the film, which is determined by the choice of material, is not so critical as that of the thickness. There are several materials whose refractive indices are near enough to the ideal for a range of optical glasses and whose chemical and physical properties give them reasonable permanence under ordinary conditions of use. The refractive index of an anti-reflection film is always less than that of the same substance in its natural form.

Silica itself has rather a high refractive index but is suitable for very dense glasses.

The metallic fluorides, calcium fluoride (fluorite), sodium aluminium fluoride (cryolite) and magnesium fluoride cover between them the whole range of optical glasses.

There are three methods by which the films are produced, two chemical and one physical. The chemical methods make the anti-reflection film out of the glass itself by dissolving away some of its constituents to a uniform depth. In the physical process the film material is evaporated on to the glass surface in a high vacuum.

§232. Chemical Methods

The original chemical method is the same in principle as the natural " weathering " which produces " tarnish ". That weathering of the right kind can increase transmission has been known, though not always to the user, for a long time. The advantageous effect of transparent tarnish was first recognised by Dennis Taylor (1896). He gave as an example a gain in transmission of 5% to 6% for a plate of Dense Flint glass after it had acquired a coloured film.

The method now used is an accelerated and controlled weathering. The oxides which are combined with the silica to give the glass its character are dissolved out with a dilute acid, leaving a skeleton of silica which makes the antireflection film. The polish of the surface is not affected, and since the film is part of the glass it is very hard and adherent. The method is, however, only workable when the glass contains a sufficient proportion of soluble constituents such as lead or barium bases.

Details of acid concentration and rates of film formation for various glasses are given in a paper by Jones and Homer (1941).

§233. A more recent chemical method (*R.C.A.* 1942) relies on the action of hydrofluoric acid vapour. The glass surface is simply sus-

pended above a dilute solution of hydrofluoric acid and care taken to prevent condensation on the glass and convection currents.

This method is not applicable to all glasses, but it has the advantage over the first method of giving a more efficient optical effect on the less dense glasses. Unfortunately the acid vapour causes etching with some glasses.

§234. Physical Method

The physical method (British Patent No. 538272) works on the same principle and requires the same apparatus as the high-vacuum process for metal-on-glass mirrors (see page 150). The chosen fluoride is powdered and evaporated from a trough on to the optical surface suspended face downwards above it. Since the material radiates from the source in straight lines, it is merely a matter of geometry to arrange for a sufficiently uniform film to be deposited. A window is required in the vacuum vessel so placed that the reflection of a white light can be seen in the surface to be coated. The light should fall on the surface at the same angle as will the traversing beam when the surface is in use.

§235. The chief advantage of the physical method is that a film material can be chosen to suit the refractive index of any glass without reference to the chemical composition of the glass. The first chemical method requires a soluble base content and is efficient only on dense glasses; the second is only applicable to glasses which do not etch. Moreover, with the physical process the thickness of the film can be observed while it is being applied. Also, the film is easily removed, leaving the glass surface unaffected. With the chemical processes the rate of growth of the film depends on the type of glass and the film is not observable during the action. As the surface of the glass itself is utilised to make the film, the film can only be removed by polishing away some of the glass.

On the other hand, the chemical methods require no elaborate apparatus and impose no strict limitation on the area of glass which can be treated as does the vacuum vessel of the physical process. Another important advantage is that the film is very durable.

In general, the physical process is most suitable for instrument components and the chemical processes, especially the hydrofluoric acid method, for single large sheets such as window glass. The exposed outer surfaces of instrument lenses or windows are sometimes provided with the chemical silica film.

When applied to the air-glass surfaces of the components of optical instruments, the anti-reflection film treatment increases transmission and contrast and eliminates ghost images. A typical result is the reduction in flare obtained by treating camera lenses (Cartwright, 1940.)

§236. It must be remembered that any contamination such as a thin layer of grease, a finger-mark or a liquid on the film, annuls its property of non-reflection. Care must also be taken to avoid abrasion, especially with the evaporated films. Grease or other stains on the film can be polished off with a very soft cloth, provided that the anti-reflection film is an adherent one, but the adherence cannot always be relied upon.

APPENDIX C

TEMPERATURE VARIATION OF THE MOBILITY OF GLASS, POLISHING PITCH, MALLET PITCH, ALLOYS, AND OTHER VISCOUS MATERIALS WITHIN THEIR ANNEALING RANGES

§237. I have had a good many experiments made on the variation of mobility with temperature of polishing pitches and mallet pitch. A strip of the material 0·08 in. thick × 0·25 in. wide (2·03 × 0·35 mm.), 6 mm. of the strip is allowed to bend in an apparatus similar to that described below.

For this purpose apparatus and method are used similar to that worked out by me in connection with the annealing of glassware, and of optical glass, which has been in use in England since 1916 and is partly described in a paper by me before the Society of Glass Technology (Twyman 1917). It is worth while giving here a description of the method as applied to the annealing of glass since the same principles apply not only to measuring the viscosity of pitch and similar materials but also to determining to what temperature objects held in position by such materials (*e.g.* blocks of lenses, thin metal articles required to be ground flat on an ordinary grinding machine, achromatic lenses and combinations of prisms cemented together with Canada Balsam) should be raised and at what rate they may be cooled in order that they may be rendered free from strain.

§238. Annealing Temperature

The apparatus described below was designed to enable the annealing temperature to be found with great accuracy, very simply, and with a delay of only an hour or so.

The importance of knowing accurately the annealing temperature for a glass seems still to be insufficiently appreciated. My experiments showed that if, at a temperature of 500° C., satisfactory annealing of a particular glass will occur in one hour, then at a temperature of 420° C. it would take 1,000 hours for the same degree of annealing to be attained. Such is the disadvantage of not heating to a sufficiently high temperature.

If, on the other hand, the temperature is taken unnecessarily high, there are also grave disadvantages. First, the glass may get too soft, so that the articles go out of shape. Secondly, there is a loss of time consequent on raising the temperature unnecessarily high and allowing it to fall again to the lower temperature which would suffice. Thirdly, it is necessary not only to anneal the glass, but to secure that faulty

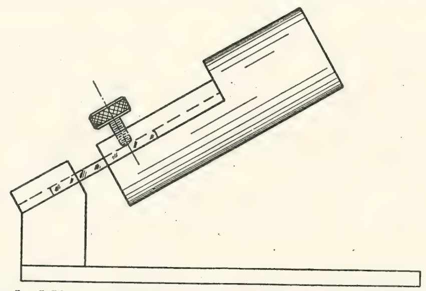


FIG. 65. Jig for holding specimen in Twyman Apparatus for Determining Annealing Temperature.

annealing is not reintroduced in cooling. If the temperature is raised only just sufficiently high for annealing to take place, the temperature will naturally fall slowly through the range within which faulty annealing may occur. When the temperature has got below that range, it is impossible to reintroduce want of annealing by means of cooling, however rapid; the cooling may even be so fast that the articles are fractured without any permanent strain being introduced. If, however, the temperature is taken unnecessarily high, it will naturally be falling rapidly throughout the very range where slow cooling is essential.

These considerations show how important it is that the annealing temperature of every glass used by a manufacturer should be accurately known to him. Even the variations of glass from the same furnace week by week are important and should be followed by corresponding variations in the annealing lehr if the best and quickest annealing is to be attained.

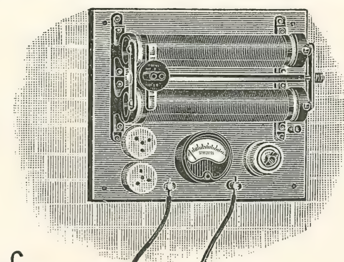
§239. Best Rate of Cooling

A piece of glassware may be cooled down from the annealing temperature in a given time, in a great variety of ways. There is one way which is the best—one way, namely, which will give better annealing than any other.

§240. Description of the Apparatus

The apparatus is shown in the figure and consists of an electric furnace (*C*), a pyrometer and temperature indicator, illuminating lamp (*A*), telescope (*G*), and a jig for holding the strip of glass, metal or other material under test.

The jig is of nickel, and is so constructed (Fig. 65) that one end of a small strip of the glass may be slipped into a socket, while to the other end is fixed a weighted arm. The inclination of the arm therefore measures the bending of the strip; and this inclination is observed and measured by the telescope (*G*), which has a reference line in the eyepiece, which can be turned into any orientation, its rotation being measured on a divided circle.



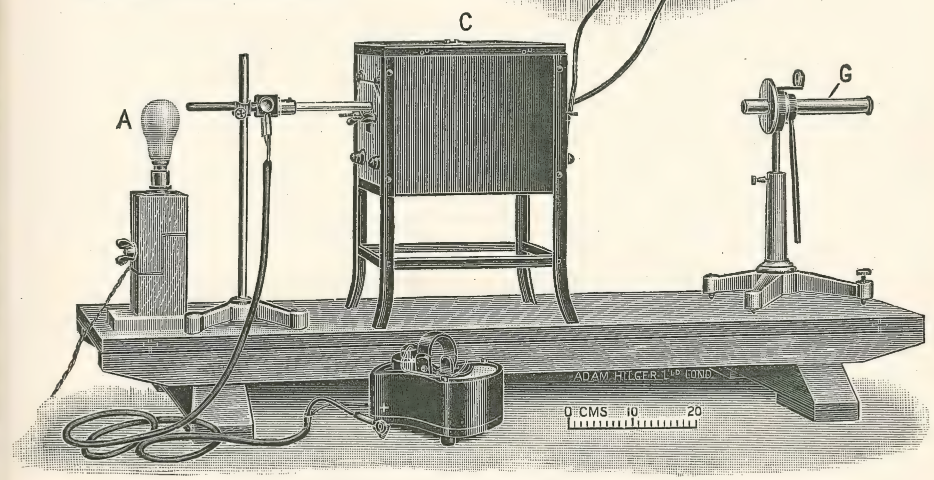


FIG. 66. Twyman Apparatus for Determining Annealing Temperatures.

§241. To Determine the Annealing Temperature of a Glass

From the piece of glass, the annealing temperature of which is required, a strip is ground 6·0 mm. wide by 2·0 mm. thick, and about 15 mm. long, the precise length being unimportant. This is clamped in the jig (Fig. 65) in such a way that 6·0 mm. of its length is free to bend. To the free end is firmly clamped the nickel bar bearing the weight *F*. The jig is placed within the electrical tube furnace, illuminated by light from the frosted lamp *A* and viewed by the telescope *G*, an image of the nickel bar being seen in the eyepiece of this telescope. The telescope can be rotated about its axis, the rotation being measured by a divided circle, and by means of a line seen in the eyepiece of the telescope the deflection of the nickel bar to which the weight is attached can be measured from time to time. The pyrometer, by means of which the temperature of the furnace in the neighbourhood of the glass strip can be continuously observed, should be placed as near as possible to the

glass strip within the furnace, without obscuring the view in the telescope of the nickel bar, by observation of which the bending of the glass strip is observed.

Method of Observation

The furnace is heated until a definite movement of the nickel bar is observed, and the line in the telescope set to lie along the image of the bar of nickel, the deflection of this bar in, say, a quarter of an hour is observed, the temperature being kept uniform during this time.

Calculation and experiment have shown that a rate of deflection of the lever of 2·2° per hour is obtained at a temperature of the furnace which will rapidly and perfectly anneal samples of domestic or chemical glassware. This corresponds with a release of 95% of the strain in three minutes.

The annealing temperatures of glasses vary very much. I find among my notes the following:

Kind of Glass.	Annealing Temperature.
Soda Glass Tube - - - - - -	500° C.
Schott's U.V. Glass - - - - - -	512° C.
Boro Silicate Crown - - - - - -	540° C.
Dense Flint - - - - - - -	465° C.
Double Extra Dense Flint - - - -	390° C.
Pyrex Tube - - - - - - -	588° C.
Dense Barium Crown - - - - - -	637° C.

The reader is warned against supposing that glasses as designated above will always have the same annealing temperature. "Dense flint", for example, is a very loose phrase which may cover a wide range of glasses.

Rate of Cooling

In cooling glass, once a temperature of 80° C. below the annealing temperature has been reached, no detriment to the annealing can arise whatever the rate of cooling may be. The only precaution to be observed is that breakage should not occur.

But the mode of cooling throughout the first 80° C. is of great importance. The tables *a*, *b*, *c*, *d* and *e* below give different rates of fall of temperature, each of which produces *the best annealing that can be produced in the respective times.*

It goes without saying that passable annealing can be and often is attained without strict adherence to this form of cooling curve; much annealing is still done without adequate means of control of the falling temperature. But where there is such control both the speed and the certainty of perfection of the annealing process can be very greatly improved by using this exponential form of cooling curve.

Assuming such control, that cooling curve should be selected which,

for the glassware under treatment, gives satisfactory annealing in the shortest time.

Range of Controlled Cooling

The range below the annealing temperature throughout which the cooling must be controlled depends on the rate of change of viscosity with temperature.

With glass the viscosity-temperature relation is $M = k \times 2^{\theta/8}$ where M is the mobility, which is the reciprocal of the viscosity, k is a constant depending on the glass and θ the temperature. Thus, when the temperature has fallen 80° C., the viscosity has become 1000 times as great. In the case of pitch, instead of 8 in the above equation we must write 1·75 and the range of controlled cooling must, therefore, be for 17·5° C. below the annealing temperature, when the viscosity will have become 1000 times as great.

COOLING SCHEDULES

(*a*)		(*b*)		(*c*)		(*d*)		(*e*)	
Time in Min.	Fall of Temp.	Time in Min.	Fall of Temp.	Time in Min.	Fall of Temp.	Time in Min.	Fall of Temp.	Time in Min.	Fall of Temp.
0	0	0	0	0	0	0	0	0	0
1	·6	2	·6	3	·6	4	·6	5	·6
2	1·3	4	1·3	6	1·3	8	1·3	10	1·3
3	2·0	6	2·0	9	2·0	12	2·0	15	2·0
4	2·7	8	2·7	12	2·7	16	2·7	20	2·7
5	3·5	10	3·5	15	3·5	20	3·5	25	3·5
6	4·3	12	4·3	18	4·3	24	4·3	30	4·3
7	5·2	14	5·2	21	5·2	28	5·2	35	5·2
8	6·2	16	6·2	24	6·2	32	6·2	40	6·2
9	7·3	18	7·3	27	7·3	36	7·3	45	7·3
10	8·5	20	8·5	30	8·5	40	8·5	50	8·5
11	9·8	22	9·8	33	9·8	44	9·8	55	9·8
12	11·3	24	11·3	36	11·3	48	11·3	60	11·3
13	13·0	26	13·0	39	13·0	52	13·0	65	13·0
14	15·0	28	15·0	42	15·0	56	15·0	70	15·0
15	17·5	30	17·5	45	17·5	60	17·5	75	17·5
16	20·5	32	20·5	48	20·5	64	20·5	80	20·5
17	24·7	34	24·7	51	24·7	68	24·7	85	24·7
18	31·4	36	31·4	54	31·4	72	31·4	90	31·4
19	44·1	38	44·1	57	44·1	76	44·1	95	44·1
19¼	80·8	38½	80·8	57¾	80·8	77	80·8	96¼	80·8

Other cooling schedules, quicker, slower, or intermediate, can be deduced from (*a*) by multiplying all the times by a constant factor.

These tables are calculated as follows :

Theoretical considerations based by me on my observations of the varying viscosity of glass with temperature (Twyman 1917) and of the stress observed to result from cooling show that the best annealing can be attained in a given time if the cooling follows the following formula connecting time and temperature :

$$t=\frac{1}{mb}\left\{1-\frac{1}{e^{m(\theta_0-\theta)}}\right\} \quad (1)$$

where $m=0{\cdot}0865$.

b is a factor by the variation of which quicker or slower schedules of cooling are arrived at.

θ_0 is the correct annealing temperature as found by the apparatus.

e is base of the Napierian logarithms.

and t is the time taken to fall from the annealing temperature to temperature θ.

Temperatures to be measured in degrees Centigrade. If b is the rate of cooling per hour, t is in hours ; if b is the rate per minute, t is in minutes.

Alternatively the formula (1) may be written

$$\theta_0-\theta=\frac{\log\left(\frac{1}{1-m\,bt}\right)}{m\log e}. \quad (2)$$

APPENDIX D

LIST OF NAMES OF MATERIALS AND GLOSSARY OF TERMS USED IN PRISM AND LENS MAKING

Abrasives—Grinding materials.

Aloxite, **Alundum**—Artificial corundum.

Angling—Grinding angles correctly on a block of material.

Back reflecting 'scope—Angle Dekkor or auto-collimator, used for final tests in angling.

Beeswax—Used as a constituent of cements and polishers.

Benzene (petrol) (known in U.S.A. as gasoline)—Used for cleaning.

Blocking—Preparing groups of objects for simultaneous grinding or polishing.

Canada Balsam—Adhesive material used in uniting optical components.

Carborundum—Silicon Carbide (SiC), an abrasive.

Chamfer—Small bevel made at the edge of a polished surface to prevent chipping.

Chromium Oxide—A polishing powder.

" Coates Cement " (see de Khotinski)—Workshop name for de Khotinski cement.

Contacting—Strictly, placing of surfaces in optical contact, but used loosely for placing surfaces together within a few rings.

Corundum—Natural aluminium oxide, used for an abrasive (Al_2O_3).

Creosote (coal tar)—In U.S.A. called " creosote oil " or " liquid pitch oil ".

Crystolon—An artificial corundum.

Diamantine—A polishing powder.

Diamond—Used in various forms. The less fine grades are also called " bort ".

Edging—Reducing lens to correct diameter or shape by grinding.

Emery—General term for the finer abrasives, called, in order of fineness, trueing, fine trueing, smoothing and fine smoothing.

Fuller's Earth—Used with rouge in polishing on cloth polishers.

Gas Pitch—In U.S.A. usually called " coal tar pitch ".

Goniometer—Device for measuring or gauging angles.

de Khotinski Cement (in U.S.A. made as Cenco Sealstix)—A useful cement for cells, etc.

Knocking-off—Removal of lenses or prisms from block.

Mallet—Small blob of mallet pitch used in blocking.

Ochre, Red, **Ochre, Yellow**—Materials used with pitch in the preparation of " mallets ".

O.G.—Object glass or lens.

Optical Contact—Such close mutual contact between surfaces that they adhere without reflection.

Paraffin (in U.S.A. called kerosene)—Used as a lubricant in slitting.

Paraffin Wax—Used for polishers.

Petrol (in U.S.A. called gasoline)—Used for cleaning.

Pitch, Gas—Used for polishers.

Pitch, Swedish (in U.S.A. called " Stockholm pitch ")—Used for polishers.

Portland Cement—Used with plaster, for blocking in plaster.

Proof Plate, plane or glass—Plate of glass or quartz accurately flat or of determined curvature, used for testing accuracy of surfaces by Newton's rings.

Putty Powder (tin oxide)—Used as polishing powder.

Plaster of Paris—Used for blocking prisms.

Protectors—Pieces of glass cemented to a face adjacent to that being smoothed or polished, and forming an extension of the surface being worked, thus enabling the whole surface to be worked without the edge chipping or rounding.

Red Ochre—Used as a constituent of " mallet pitch ".

Rosin (in U.S.A. called " colophony ")—Used as a constituent of various cements.

Rouge—Red oxide of iron, ferric oxide (Fe_2O_3), used as polishing powder.

Rouge, Jewellers' (see Rouge).

Roughing—The first stage of grinding following slitting or shanking.

Sawdust, Willow—Used in preparing wax polishers.

Shanking—Reduction of glass to shape by chipping with shanking shears.

Sira Abrasive—Developed by the British Scientific Instrument Research Association.

Sleeks—Very fine scratches.

Slitting—Cutting glass to shape with a diamond impregnated disc.

Smoothing—Third stage of grinding following trueing and preceding polishing.

Swedish Pitch (see Pitch).

Trueing—Second stage of grinding, following roughing; correcting tools by grinding them together.

Test Plate—Proof plate, *q.v.*

Wax, Paraffin—Used for cementing prisms to a block.

Windolite—A glass substitute used for dust screens.

Window—A plane disc of glass through which light is transmitted; may be parallel or deviating.

Wood Pitch (see Pitch).

Yellow Ochre—Used as a constituent of " mallet pitch ".

A SHORT GLOSSARY OF FRENCH WORKSHOP TERMS, USED IN THE PARIS OPTICAL TRADE, AND WHICH ARE NOT GENERALLY FOUND IN THE USUAL TYPES OF FRENCH-ENGLISH DICTIONARIES

Adapted in part from Dévé (1936). Translation by Major W. M. G. Thom.

Balle—A convex tool, *i.e.* to generate concave surfaces.

Bassin—A concave tool, *i.e.* to generate convex surfaces.

Barre Ponte—A bridge bar on a grinding or polishing machine to carry testing, etc. appliances or attachments, for use without removing a job from the machine.

Berzélius—Unsized paper for polishing (a kind of blotting paper).

Bloc and Blocage—Block and Blocking.

Bosse—Convex surface of a plano-convex lens, etc. (Commonly spoken of as the " vex side ".)

Brisoir—Bruiser—tool for breaking down and spreading abrasive.

Brucelles—Spring tweezers, forceps, etc. (Slang—pince-nez.)

Caillebotter, Plateau à—Tool with circular grooves for rough grinding and shaping small convex lenses.

Calibre—Proof plane or sphere.

Calotte—A double-sided type of spherical metal tool with a movable handle, for rough grinding to size, either concave or convex, according to the position of the handle.

Carotte—Cylinder of discs cemented together for edging *en masse*.

Chair—Granular appearance under magnification, of an imperfectly polished surface (*i.e.* fine grinding defective). Grey.

Colloir—Squeegee for pressing out cement or adhesive under paper polishers, while being fixed to the tool or runner.

Cotret—Small pencil-shaped holder on which small lenses are cemented for working.

Couleurs, Travail au—Working to proof planes or spheres by Newton's fringes.

Couronne—Region which surrounds central region of the surface of a lens, etc.

Courte—Used of a surface whose curvature is too strong, that is, of short radius, *i.e.* which has been worked beyond its correct curvature.

Cuirasse—Strips of cardboard, tin, sheet-metal, etc., cemented to a curved tool, to modify its curvature, for a polisher, block tool, etc.

Déborder—Edging.

Déglanter, Maillet à—Knocking-off mallet.

Dégrossisage—Roughing.

Doucissage—Smoothing, final grinding before polishing.

Dopp—Holder for working a diamond.

Ebauchage—Trueing, the second stage in grinding.

Echignures—Digs on an optical surface (literally claw marks).

Eclaircir—Preliminary stage in polishing.

Egrisé—Diamond dust—generally in olive oil, vaseline, etc.

Equarrir, Pince à—Shanks, used for shaping a piece of glass by chipping the edge to a disc of about the right dimensions.

Fausse Equerre—Bevel gauge.

Filandres—Sleeks.

Fils—Striations in glass, veins. Spoken of as " sec " or " gras " according to whether they are sharply defined or diffuse.

Fioner (pince à)—Flonk, or allied percussion tool, whereby the surface of a piece of glass is flaked roughly to curvature, to save grinding.

Frayure—Slight graze or scratch. (Intermediate between a scratch and a sleek.)

Gaufrage—Operation of shaping to curvature, cloth, felt, pitch-saturated taffeta, etc., for a polisher.

Gland—Pitch Mallet, as in blocking.

Glanter—Operation of pitch malleting.

Gris—Incompletely polished (say $\frac{3}{4}$ths) surface, which has been properly fine ground.

Grès—Natural grit or sand, and also, occasionally, the natural emery sands which occur in Asia Minor and Macedonia.

Hirondelle—Jig in which Iceland spar is cut in the manufacture of Nicol prisms.

Système " Jarret "—Method of testing prisms in the workshop, by fringes, using an optical flat, based on the algebraic sum of the fringe systems. A modification of this is used to test prisms for pyramidal error.

Jeune—Surface not yet brought up to proper curvature—opposite of " courte ".

Minutage—Process of washing and grading an abrasive by elutriation.

Molette—Wooden handle on which a small lens is worked individually.

Miroitier, Pince à—See Equarrir, Pince à.

Mouche—The concavity ground in " spotting for thickness ".

Nonius—Calliper with a scale, but without vernier, used in " spotting for thickness ". Also a double-ended calliper used in conjunction with a wedge or " step " gauge, for the same purpose.

Perçage—Drilling small holes in glass.

Pierre d'Aiguiser—Oilstone, water stone, Water of Ayr stone, etc.

Pierre de Levant—Turkey Stone—natural emery stone.

Plateaux—Flat tools.

Points Crevés—Bubbles in glass brought to the surface during grinding and polishing.

Procèdé " Jarret "—See Système " Jarret ". The former term is the less commonly used.

Raffinage—Increased fineness acquired by an abrasive during the working process between a tool and glass.

Rainer—Edging a lens, etc., with a peripheral groove, to take a special mounting, etc.

Réunir—Regrinding pairs of tools to again bring them to correct curvature; generally done by hand.

Rose à Polir—Cerium oxide.

Rouge à Polir, **Rouge Anglais**, **Colcotar**—Polishing rouge (ferrous oxide).

Saccade, Par—" By intermittent touches ", as in drilling glass by tube or hollow mill.

Sciage—Sawing or slitting glass.

Séchée—A " Wet " (literally a " dry ") in polishing.

Surfaçage—The combined processes of fine polishing and grinding, but exclusive of roughing.

Tournette—" Banjo " or similar machine for cutting circles by diamond, in sheet or plate glass.

Valseur—Planetary geared head of a grinding or polishing machine, generally fixed to a " barre ponte " and driven through a flexible shaft.

TERMS USED IN CONNECTION WITH THE OPTICAL WORKING OF CRYSTALS

Macle—(1) Workshop slang for wrongly cemented prisms of quartz, *i.e.* for example, a Cornu prism when two components of similar optical qualities are cemented together in error.
(2) An intolerable natural defect in a crystal whereby a small crystal has been engulfed, *in toto*, by a more rapidly growing, or later growing, larger crystal.

Niège—A cloud of defects within a crystal, having the appearance of matte snow-flakes.

Vacuole—Natural void within a crystal, having a similar appearance to a bubble in glass.

APPENDIX E

Notes on Parallelism of Glass Plates

1 second = 0·000,0048 inches in 1 inch.
1 minute = 0·000,29 ,, ,,
1 degree = 0·0175 ,, ,,

Testing by interference (reflection) from two nearly parallel surfaces separated by air or by glass :

1 band by mercury green light (air between the surfaces) indicates 0·000,0107 inches out of parallel.

1 band by mercury green light (glass, refractive index 1·52, between the surfaces) indicates 0·000,0071 inches out of parallel.

Angle between Surfaces (A)	No. of Dark Bands per in. by Reflection (Air between Surfaces) $=\frac{2t}{\lambda}$	No. of Dark Bands per in. by Reflection (Glass between Surfaces) $=\frac{2\mu t}{\lambda}$	No. of Dark Bands per in. by Double Trans-mission $=\frac{(2\mu-1)t}{\lambda}$	Deviation (produced by Back-Surface Reflection) $=2\mu A$	Deviation (Single Trans-mission) $=(\mu-1)A$
1 sec.	0·45	0·7	0·2	3·0 secs.	0·5 sec.
5 secs.	2·2	3·4	1·2	15·2 ,,	2·6 secs.
10 ,,	4·5	6·8	2·3	30·4 ,,	5·2 ,,
15 ,,	6·7	10·2	3·5	45·6 ,,	7·8 ,,
20 ,,	8·9	13·6	4·6	60·8 ,,	10·4 ,,
25 ,,	11·2	17·0	5·8	76·0 ,,	13·0 ,,
30 ,,	13·4	20·4	7·0	—	15·6 ,,
35 ,,	15·6	23·8	8·1	—	18·2 ,,
40 ,,	17·9	27·2	9·3	—	20·8 ,,
45 ,,	20·1	30·5	10·4	—	23·4 ,,
50 ,,	22·3	33·9	11·6	—	26·0 ,,
55 ,,	24·6	37·3	12·8	—	28·6 ,,
60 ,,	26·8	40·7	13·9	—	31·2 ,,

Refractive Index $\mu = 1{\cdot}52$.

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A

Abbe, E., 139
Adcock and Shipley, 44, 45, 72, 73
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Airy, G. (1834), *Trans. Camb. Phil. Soc.*, **5**, 283
Aristophanes, 9
Arnulf, Albert, 130
Atelier de Construction de l'Artillerie, Puteaux, 66

B

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Brashear, 145
Bratke, 98, 119
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Bruhat, G., 115
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Bullet, Nicholas, 1

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Chalmers, 119
Chalmers (1912), *Proc. Opt. Convention*, 56
Chance Brothers & Co. Ltd., 131, 132, 134
Cicéron, 9
Clark, Alvan, 119
Claude-General Neon Lights, Ltd., 145
Cooke, Troughton and Simms, Ltd., 93
Crommelin, C. A., 7
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Czapski, 119

D

Dalladay, A. J. (see also Twyman), 17, 129, 133
Dalladay, A. J. and Twyman, F. (1921-2), *Trans. Opt. Soc.*, **23**, 165.
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R. C. A., 153
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Ridler, K. E. W. (see Bowden and —), 18
Ritchey, G., 36
da Rivalto, Giordano, 1
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Ronchi, Vasco, 98, 119
Ronchi, Vasco (1926), *Z. Instrumentenk.* **46**, 553
Ross, Ltd., 101
Rosse, Lord, 8

S

Sabine, G. B., 152
Sabine, G. B. (1939), *Phys. Rev.*, **55**, 1064
Schroeder, 119
Schuster, A., 114
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Simeon, F., 133
Smith, T., 125
Stafford Allen and Sons, Ltd., 78
Strong, J., 11, 14, 17, 149, 150, 151
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Suétone, 9

T

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U

Underhill, S. J., 57
United Kingdom Optical Company Ltd., 36
University of Melbourne, 127

W

Waetzmann, 98, 119
Watson Baker (see Disney, etc.)
Whitworth, Sir J., 24
Wilde, E., 1, 9
Wilde, E. (1838 and 43), *Geschichte der Optik*. (Berlin)
Winfried, 9
Wright, F. E., 14
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Z

Zeiss Carl, Ltd., 40, 41
Zeiss, Carl, Ltd. (1907), Brit. Pat. Spec. 14,126/07

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S

T

U

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ERRATA AND ADDENDA

Page 13, line 3. *Instead of* " $\frac{1}{8}$ inch thick " *read* " $\frac{1}{4}$ to $\frac{3}{8}$ ins. thick ".

P. 13, l. 12. *Instead of* " gauze 20 mesh to one inch " *read* " gauze 16 mesh to one inch ".
(An even coarser mesh up to 10 mesh per inch can be used.)

P. 21, l. 14. *Instead of* " done with trueing emery " *read* " done with smoothing emery ".

P. 21 (§ 38) l. 10. *For* " $r = \frac{s^2}{2d} \times \frac{d}{2}$ " *read* " $r = \frac{s^2}{2d} + \frac{d}{2}$ ".

P. 24, l. 16. *For* " the constant α " *read* " the constant a ".

P. 24 (§ 42) ll. 7 and 8. *Read* " These must be of radii respectively less and greater than the radius of the tool. . . ."

P. 28, l. 13. *For* " ·7 " *read* " 3·7 ".

P. 30 (§ 56) l. 10. *For* " less viscous " *read* " more viscous ".

Page 52, last l. " . . . leave blocks until cold ". It is more usual practice to commence smoothing while the block is still warm and the mallets are slightly plastic so that they settle into place.

P. 67 (§ 126). Sleeks, digs and scratches may be defined as:
Sleeks . . . will polish out in 3 to 4 wets.
Scratches . . . will smooth out in the block.
Digs . . . require hand trueing singly for their removal.

P. 72, top. l. *For* " V " *read* " L ".

P. 73 (§ 134), l. 2. *After* bracket *insert* " or diamond wheel 200 grit ".

P. 82 (§ 152), l. 11. *After* " *i.e.*, flat " *insert* " or slightly concave ".

Pp. 119 and 167. *For* " Birch " *read* " Burch ".

P. 135, l. 12 from bottom. *For* " latter " *read* " former ".

P. 141, (§ 212), top. l. *For* " 64 " *read* " 62 ".

P. 166. *For* " $\frac{(2\mu - 1)t}{\lambda}$ " *read* " $\frac{2(\mu - 1)t}{\lambda}$ ".

P. 168. *Under* " Hampton " *delete* " (2nd Edn. 1841) ".